THE INFLUENCE OF TIDAL INLET MIGRATION AND CLOSURE ON BARRIER PLANFORM CHANGES: FEDERAL BEACH, NC

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ABSTRACT

Federal Beach, a narrow 10 km-long barrier spit that connects the Fort Fisher headland and the Cape Fear foreland, has been breached numerous times during the past centuries. Prior to 1880 the storm breaches served as one of several conduits for the exchange/discharge of the Cape Fear River. One long-lasting breach that opened in 1761 near the headland evolved into the second largest inlet system in the area until it was artificially closed by the U.S. Army Corps. of Engineers in 1880. Closure was accomplished by the construction of a 4.6 km-long dam that dramatically reduced the tidal prism and the extent of the ebb tidal delta. Long-lasting impacts associated with inlet closure include the chronic erosion of the headland area and frequent breaching of the barrier and the subsequent rapid migration of small inlets. Concurrent with inlet migration is the realignment of the barrier spit shoreline.

A GIS-based analysis of aerial photographs from 1938 to 2005 was conducted to quantify shoreline rate-of-change values for the barrier spit, and migration rates of the associated inlet systems. The Federal Beach barrier spit shoreline accreted an average of 6 m, at a rate of 0.1 m/yr during this period. This study identifies two shoreline change zones (SCZ). SCZ I is characterized as a retrograding reach, with long-term erosion averaging 78 m from 1945 to 2005. Over the same period, SCZ II is characterized as a prograding reach, with long-term accretion averaging 69 m.

Two inlet systems, New Inlet A (NIA) and New Inlet B (NIB) were active along the Federal Beach barrier from 1938 to 1999. The NIA system opened in the 1890's and by 1959 had migrated approximately 6 km to the south where the system closed due to shoaling of the inlet throat. New Inlet B opened in 1944 and closed in 1999. During this

period the NIB system migrated south a total of 6 km, at a mean rate of 106 m/yr. Both the size and stability of the New Inlet B system was determined to be strongly influenced by the morphology of the backbarrier environment with respect to inlet position.

As both of the New Inlet systems migrate along Federal Beach they actively reshape the barrier spit planform, resulting in the progradation of the updrift barrier shoreline. Anthropogenic and natural changes to the backbarrier environment have impacted the behavior of the inlet systems, consequently resulting in long-term changes of the Federal Beach barrier spit planform.

DEDICATION

Mom and Dad

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INTRODUCTION

Currently, over two thirds of the world's population lives within 150 km of the coast. In the U.S 54% of Americans live in coastal counties. The population density of coastal areas in the U.S. is expected to double by 2025 (SADIK, 1994). With 20,506 miles of shoreline seriously eroding within these coastal counties, there is an ever increasing need for local, state and federal governments to establish and implement effective coastal management policies.

North Carolina is just one of the many states whose coastal communities are being threatened by chronic beach erosion problems. North Carolina is experiencing one of the highest rates of population growth in the country. During the period from 1970 to 1995, the overall population of the state increased 40 percent, from approximately 5 million to 7 million. In 1995 North Carolina had the 10th highest population of all the states. This growth is expected to continue, and by the year 2020 the population is expected to exceed 9 million. As with other coastal states, much of this growth is located along the ocean shoreline (US CENSUS BUREAU, 2005).

The majority of chronic-erosion zones along the North Carolina coastline are associated with contemporary inlets or inlets that were closed artificially (CLEARY and MARDEN, 1999). Currently, inlets comprise less then 1% of North Carolina's coastline, yet, during the past two centuries, they have influenced 65% of the barrier shorelines that comprise the Onslow Bay Compartment (CLEARY and PILKEY, 1996). To mitigate this on going erosion problem, North Carolina planned to spend approximately 12 million dollars on beach nourishment for the FY 2005. Accurate prediction of shoreline retreat, land loss rates, and the cost of management alternatives is critical to the planning of coastal zone management strategies (CLEARY *et al*., 1996).

The coastal area is a highly variable and extremely dynamic environment. Physical processes, such as tides, waves and wind, are constantly reshaping the many morphological features of the coast to establish an environmental equilibrium. In addition, the underlying geologic framework, offshore topography and human activity are all reflected in the morphology of any given coastal system. Understanding the processes and three-dimensional geologic framework that govern coastal morphology is vital to determining the behavior of beaches, particularly those that have been replenished artificially (CLEARY *et al*., 1996).

Tidal inlets are openings in the shoreline through which water infiltrates the land, thereby providing a connection between the ocean and bays, lagoons, or marsh and tidal creek systems (FITZGERALD, 1996).Tidal inlets are associated with barrier systems and are found throughout the world in a variety of different environmental settings. Tidal inlets most commonly occur along passive continental margins (INMAN and NORDSTROM, 1970) with microtidal to mesotidal conditions (HAYES, 1979).

Tidal inlets are one of the most studied systems in the coastal environment. Nevertheless each tidal inlet is a unique system. The diversity in morphology, hydraulic signature, and sediment transport patterns of tidal inlets attests to the complexity of their processes (FITZGERALD, 1996). One of the problems with formulating models (numerical and conceptual) or predictive relationships concerning inlets is the difficulty in devising a model that includes a large population of inlets, while at the same time making the model sufficiently accurate to supply quantitative information needed to answer specific questions for a particular inlet or address broad management issues (FITZGERALD, 1996). Numerous investigations dealing with almost every aspect of tidal inlets have been undertaken. However, little work has been done on investigating the impact of inlet closure on shoreline change.

There have been extensive investigations into tidal inlet systems of the Georgia Bight, especially in North Carolina. Most notably are those by CLEARY and PILKEY (1996), CLEARY and FITZGERALD (2003), CLEARY and MARDEN (1999), JOHNSON *et al*. (1999), and HAYES (1994).

Investigations of tidal inlet closure in North Carolina include MCGINNIS (2004), RICE (2002) and WELSH (2004). Investigations of inlet closure outside the southeastern U.S. have been primarily focused on seasonal inlet closures (e.g. RANASINGHE and PATTIARATCHI 1999; RANASINGHE *et al*., 1999). Emphasis has been placed on determining the mechanics and relative magnitude of the physical forces governing closure. However, these studies have neglected to quantify the long-term shoreline changes associated with inlet closure.

Of the many morphological features found in the coastal system, tidal inlets are of particular importance for a number of reasons. Tidal inlets are a major influence affecting almost all physical, biological and chemical processes active in the coastal area. Tidal inlets serve a whole host of primary and secondary functions. In addition to serving as entrances to harbors, tidal inlets actively flush estuaries with sea water and nutrients, act as conduits for spawning and larval marine organisms, as well as impound a large volume of sediment thus impacting large tracts of shoreline (FITZGERALD, 1996). In short, there is little in the coastal environment that is not in some way influenced by a tidal inlet.

The stability of a given inlet is perhaps the most important factor governing management policy. Migrating inlets are a constant threat working to undermine surrounding coastal infrastructure, and disrupt designated coastal waterways. From 1989-1995, 82% of the flood insurance claims for erosion threatened buildings in North Carolina were along tidal inlet influenced shorelines (JOHNSON *et al*., 1999). The shoreline changes associated with tidal inlets are of particular importance when evaluating the long-term effects of shoreline nourishment projects. In addition, determining the migratory history of an inlet and understanding the environmental variables acting to control that migration are of paramount importance when delineating hazard zones and designating federal waterways.

STUDY AREA

Physical Setting

Nearly continuous chains of barrier islands flank the eastern and Gulf coasts of North America. This expanse of coastal barriers is the apex of the longest single development of barrier islands in the world, stretching from Cape Cod, Massachusetts to the Yucatan Peninsula, Mexico (HAYES, 1994). The island complexes found in the southeastern states of North Carolina, South Carolina, Georgia and Florida are known as the Georgia Bight.The shoreline of the Georgia Bight, which extends from Cape Hatteras, North Carolina to Cape Canaveral, Florida, is over 750 miles long (HAYES, 1994).

The Federal Beach barrier spit complex is located in southeastern North Carolina along the Onslow Bay coastal compartment (Figure 1). Federal Beach is a 9.5 km long

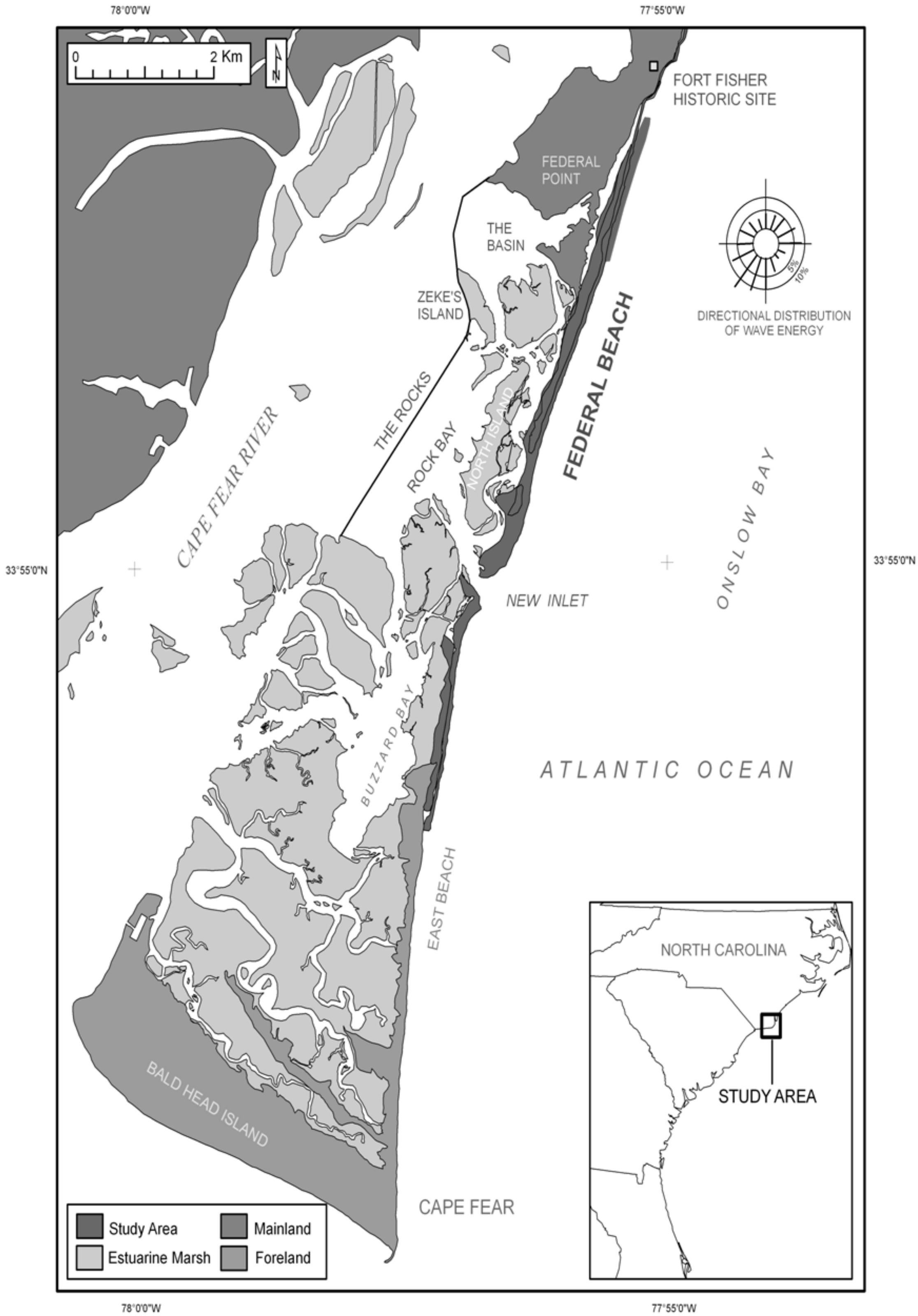


Figure 1. Locator map of Federal Beach, North Carolina. Map shows the 1987 shoreline configuration. (Wave energy data from JACKSON, 2004.)

barrier spit connecting the Pleistocene units of the Fort Fisher sub-aerial headlands to the unconsolidated Holocene sediments of the high-energy flank of the Cape Fear Foreland.

Southeastern North Carolina's coast is classified as a wave-dominated, low mesotidal barrier coast with mixed energy environments (HAYES, 1979, 1994; DAVIS and HAYES, 1984). The Cape Fear region is located in a mixed semidiurnal tidal regime. The mean tide range for the area is 1.15 m (National Ocean Service, 2005). The average wave height for the region is 0.8 m with a period of about 8.0 seconds (JARRETT, 1976).

Onslow Bay is a sediment-starved shelf system dominated by hard bottoms (CLEARY *et al*., 1996). Holocene sediment accumulation in Onslow Bay is negligible due to low fluvial input, entrapment of sediments in extensive estuarine systems and minimal sediment exchange between adjacent shelf embayments (CLEARY and PILKEY, 1968; CLEARY and THAYER, 1973; BLACKWELDER *et al*., 1982). The shoreface of the study area is characterized by hard bottoms of varying relief, morphology and lithology (Figure 2). The northern portion of the study area is dominated by the Fort Fisher subaerial headland. The coastal area here consists of a wave-cut platform incised into a series of Pleistocene sediment units with a thin beach perched on top of the irregular geometry of the Pleistocene units (MOOREFIELD, 1978; CLEARY et al., 1996).

Three major lithologies have been identified in the offshore. Erosion-resistant, lithified and cross-bedded coquina sandstone forms the Fort Fisher subaerial headland. A friable humate and iron-cemented Pleistocene sandstone fronts the shoreline south of the headland forming a 2.0 m high wave-cut cliff and terrace (CLEARY *et al*., 1996). The southern portion of the study area is a not a headland-dominated system, it is characterized by estuarine and inlet fill sediments that are much less resistant to erosion

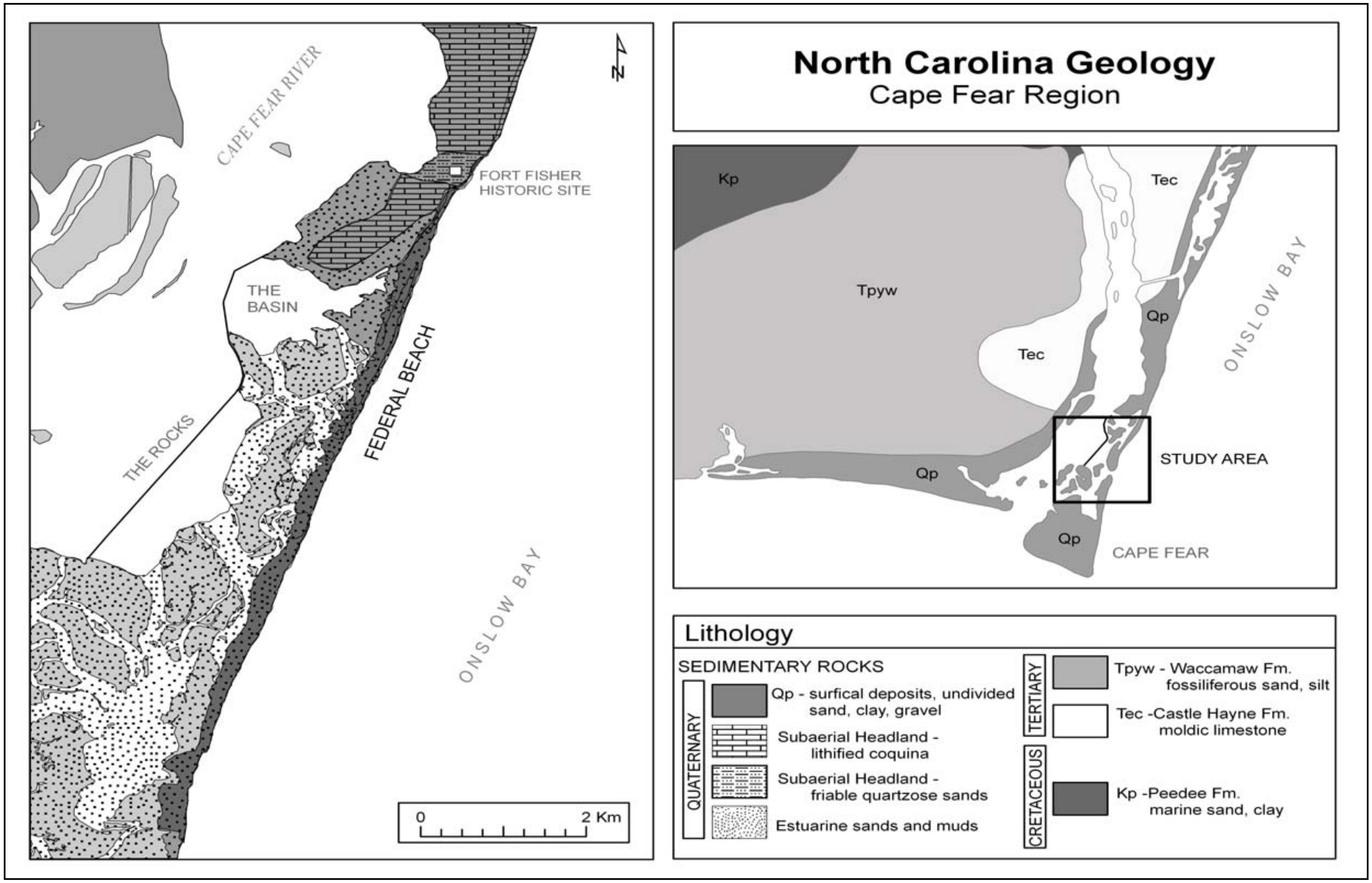


Figure 2. Map of regional geology. The shoreface of the study area is composed of a headland, a wave-cut platform and unconsolidated sediments. (Data from CLEARY *et al.*, 1996 and NC DEHNR, 1998.)

(SWAIN and CLEARY, 1992; RIGGS *et al*., 1995). The shape and evolution of the three different coastal segments around Fort Fisher is clearly related to the presence and lithology of the outcropping and underlying Pleistocene geologic framework (CLEARY *et al*., 1996).

Since 1938, there have been 58 classified storms to impact the North Carolina shore; 12 of which made landfall along the North Carolina shoreline from Bird Island to Cape Lookout (Figure 3). Hurricane Hazel was the most destructive storm to have struck North Carolina over the past 70 years (USACE, 1982). Hurricane Hazel, a Category 3 storm on the Saffir-Simpson scale, made landfall in 1954 near the North Carolina and South Carolina border. During the period from July 1996 through September 1999, four hurricanes (Bertha, Fran, Bonnie, and Floyd) ranging in scale from Category 2 to 3 storms, made landfall within the region causing substantial impacts to both beaches and property. Historically, the impact of storms along Federal Beach has been significant. The openings of one long-lasting inlet, in 1944; and several smaller ephemeral barrier breaches, in 1954 and again in 1996, were due to tropical storm activity.

In addition, extratropical storms or nor'easters have impacted the region causing substantial storm surge and heavy surf (HUDGINS, 2000; BARNES, 2001). Storm activity has been a major influence in shaping the coast of North Carolina. The energy expended and sediment transported during the few hours of a storm may equal many years of non-storm work (MORTON, 1988).

The region is dominated by southerly longshore transport. However, seasonal variations in wind and wave approach create local reversals in this trend. During the spring and summer, wind and wave approach is from the south and southwest, while

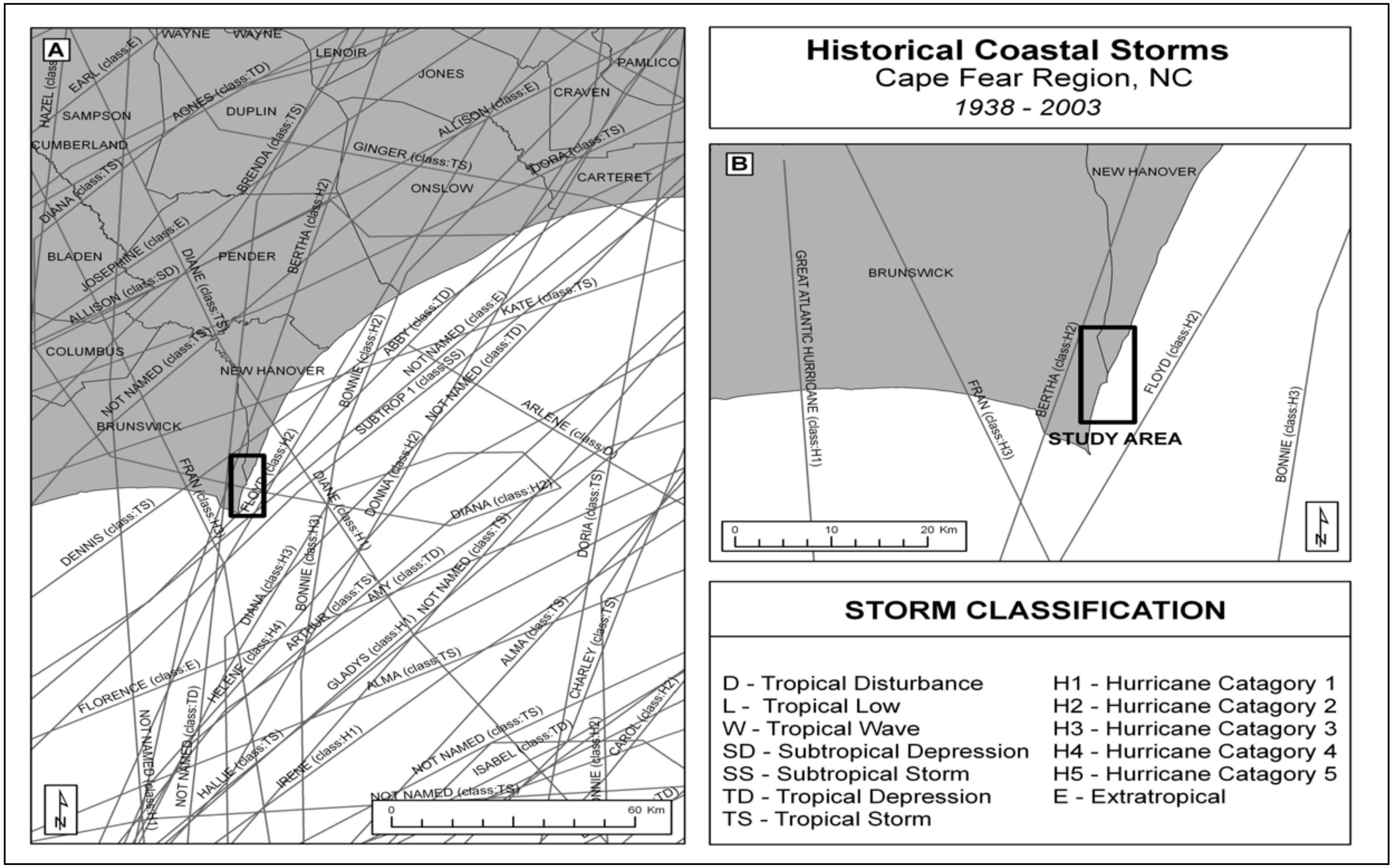


Figure 3. (a) Major tropical storms affecting southwestern Onslow Bay and Cape Fear regions from 1938 to 2003. (b) Five major storms to significantly impact the study area. (Source: NOAA)

during the winter north and northeast approaches dominate (CLEARY and PILKEY, 1996). Despite seasonal variations, the overall dominant wave approach is from the northeast resulting in a net littoral drift of approximately 230,000 cu m/ yr to the southwest (SWAIN, 1993).

History

The earliest reliable historic map of the area attained by this study was produced by MOSELEY in 1733. The map shows a long, narrow beach strand connecting the Fort Fisher headland to the Cape Fear foreland (Figure 4). In 1761, a storm of significant magnitude breached the area know as “Lower Haulover” (modern day Federal Beach), forming a new tidal inlet system (SWAIN, 1993). New Inlet, as the system became known, developed into the second largest inlet system in southeastern North Carolina.

Subsequently, New Inlet’s extensive flood-tidal delta and associated sand bodies began to shoal the proximal Cape Fear River (CFR) shipping channel (Figure 1). Initial attempts in 1852 by the U.S. Army Corps of Engineers (USACE) to mitigate the shoaling were unsuccessful. Continuous attempts to mitigate shoaling over the next thirty years, barring the extensive use of New Inlet by blockade runners during the Civil War, proved unsuccessful. Ultimately construction of a swash dam by the USACE, completed in 1887, effectively controlled the shoaling of the CFR shipping channel. Known as “The Rocks”, the dam stretched 4.5 km, from Federal Point along Zeke’s Island to Muddy Slough, and stood 30 m wide and 9 m high (Figure 1).

By 1887 however, it became evident that the impact of The Rocks was far more extensive than simple shoal mitigation. The construction of The Rocks cut the hydraulic

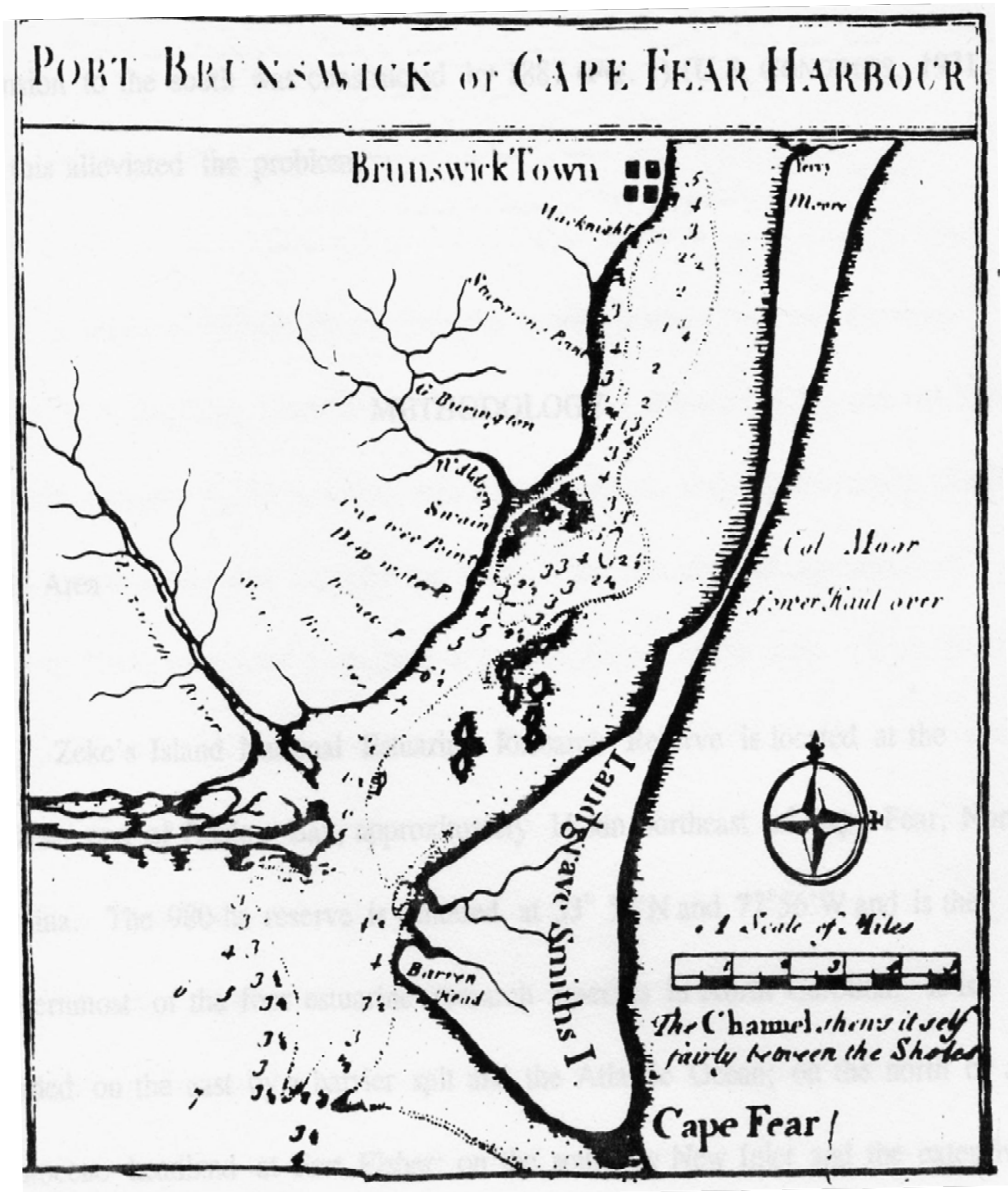


Figure 4. Cape Fear region, southeastern North Carolina as shown in “A New and Correct Map of the Province of North Carolina” by EDWARD MOSELEY, 1733.

connection between the Cape Fear River and the New Inlet system, effectively forming an artificial estuary known as “The Basin” (Figure 1). The construction of The Rocks resulted in a sharp decrease in the tidal prism of the New Inlet system. The tidal prism of the system was reduced from 58.7×10^6 m^3 in 1872 to 14.2×10^6 m^3 in 1887. Continued long-term changes in the back barrier basin capacity continued to reduce the tidal prism (SWAIN, 1993). As a result, back barrier infilling and basin sedimentation further reduced the size and stability of the system.

Concurrent to tidal prism reduction and back barrier infilling, inlet migration and barrier spit formation began reshaping Lower Haulover Beach. By 1887 New Inlet had migrated over 2 km to the south, extending the southern extent of the newly formed barrier spit by the same magnitude (Figure 5). Consequently, by 1895 the barrier spit began to overlap the existing down drift shoreline (Lower Haulover). The overlapped shoreline has remained a stable backbarrier feature and was renamed North Island (SWAIN, 1993). Originally the newly formed barrier spit was named “Carolina Shoals Beach”. The name was subsequently dropped and since then the area has had no formal name (NCDNER, 1970). This study will herein refer to the barrier spit as “Federal Beach” due to it’s proximity to Federal Point.

The construction of The Rock, the resulting migration of New Inlet and the extension of the Federal Beach barrier in 1887 marked the beginning of a sequence of cyclic, morphological changes that would be repeated until the close of the New Inlet system in 1999. The cycle, herein referred to as the “New Inlet Cycle” and summarized in Figure 6, began with the southern migration of the 19th Century New Inlet and the concurrent elongation and seaward offset of the updrift shoreline of the Federal Beach

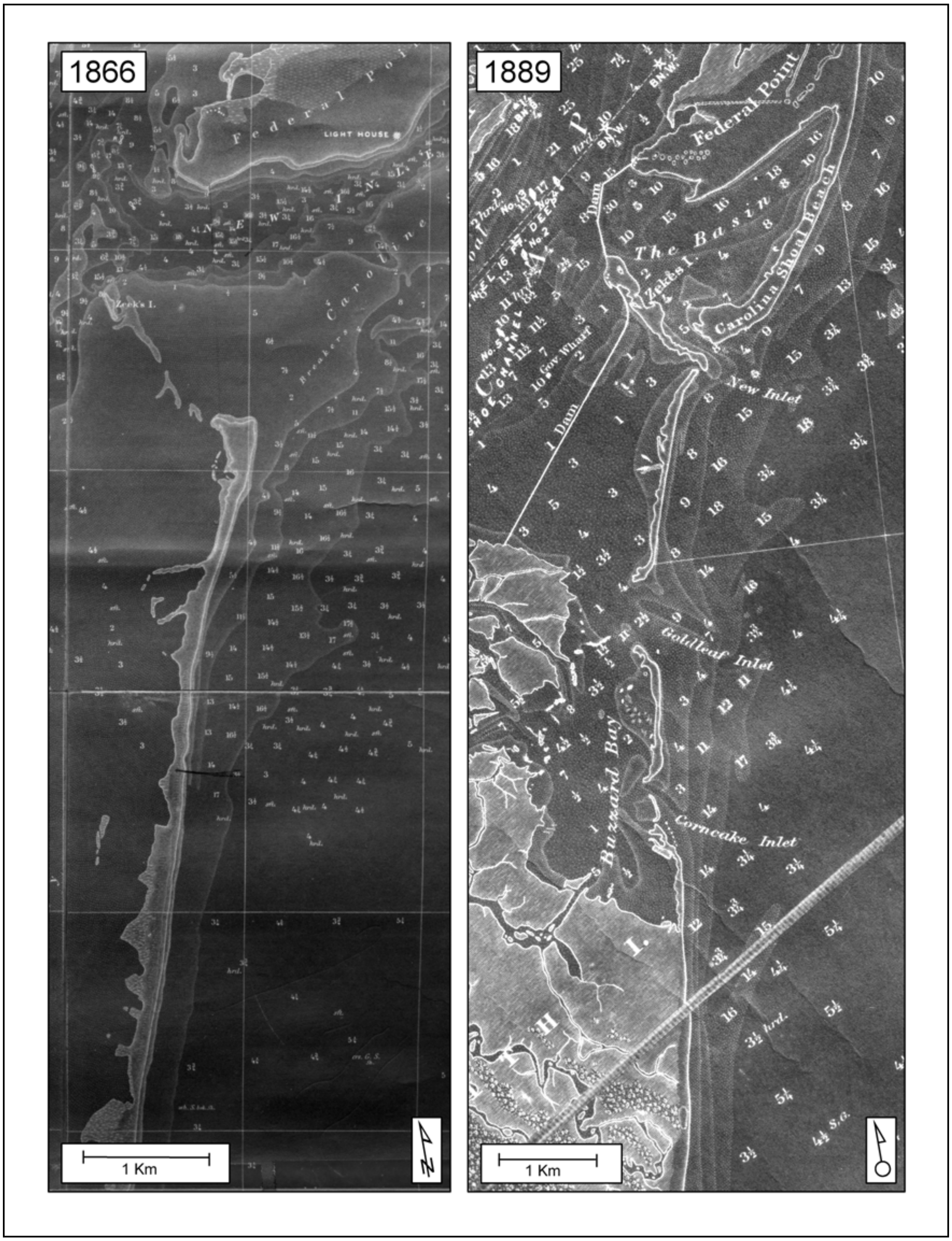


Figure 5. Image showing the pre-Rock 1866 shoreline and the post-Rock 1899 shoreline. Note the extension of "Carolina Shoal Beach" and the collapse of the ebb-tidal delta and Lower Haulover beach strand. (United States Coast and Geodeitic Survey chart)

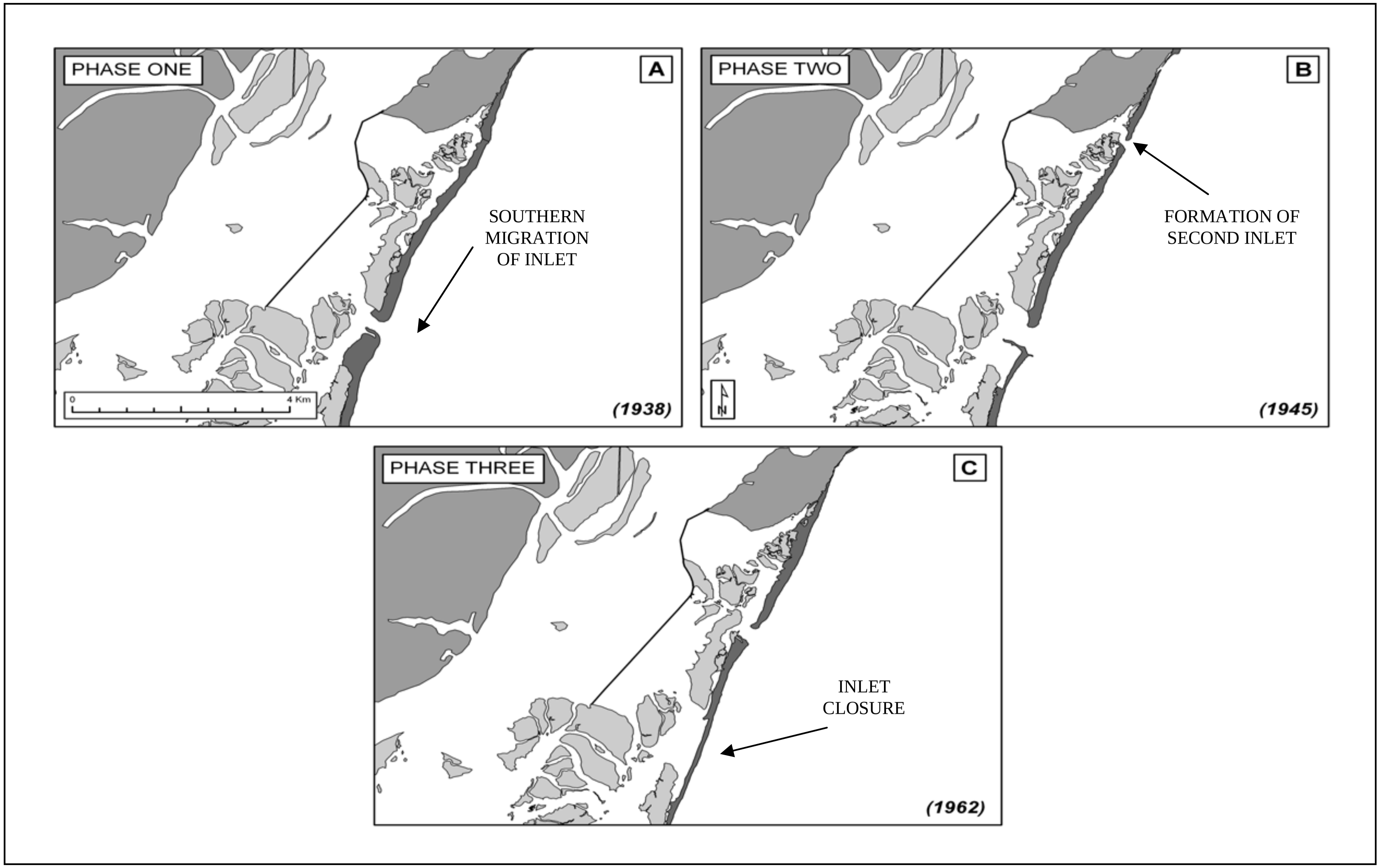


Figure 6. New Inlet Cycle showing (a) phase one, southern extension of barrier spit, (b) phase two, formation of second inlet system, (c) and phase three, closure of first inlet system

barrier spit. Continued southern migration of the inlet along North Island ultimately resulted in an elongation of the inlet channel and a reduction in the hydraulic efficiency of the system.

The second phase of the New Inlet Cycle is the opening of a second inlet. The formation of a second inlet occurred during a storm event in 1944, where the potentially large tidal prism caused a breach along the narrowest part of the Federal Beach barrier near the point of spit attachment. As is typical in this system the northern, or newest, inlet began to capture more tidal flow and effectively reduced the tidal flow of the southern, or older, inlet system.

The third phase of the New Inlet Cycle is inlet closure. Once the dominance of the northern inlet was established, the southern most inlet, due to a lack of tidal exchange, began to shoal and eventually closed. HAYES (1991) identified two processes by which inlets commonly form. In the first process, as is exemplified by the last two New Inlet systems, storm generated scour channels result in shallow inlets prone to migration. In the second process identified by HAYES (1991), an inlet forms through the closure of an estuary entrance by the growth of a barrier sand spit. This is the way in which the Carolina Shoal Beach barrier spit and associated inlet system formed after the instillation of The Rocks was completed (Figure 5).

In 1996, the USACE completed another civil works project within the study area. The USACE constructed a 926 m-long multi-layered rubble revetment fronting the Fort Fisher historic site. Since the construction of The Rocks and the collapse of the large 19th century New Inlet system and associated tidal-deltas, chronic erosion has characterized the Fort Fisher historic site. This erosion threatened the 19th century earthen works of the historic fort and the surrounding infrastructure. To mitigate shoreline erosion and prevent further loss of the historic site the USACE stabilized the shoreline via a hard engineering structure. The construction of the rubble revetment resulted in a loss of material to the littoral system and an increased shoreline erosion rate of approximately – 2.5 m/yr just south of the structure (USACE, 2004).

Since the construction of The Rocks, the Federal Beach barrier spit complex has become a multi-inlet system, with at least three inlet cycles occurring since 1887 (SWAIN,1993). The focus of the current investigation is phase two, which opened in the Great Atlantic Hurricane of 1944, and the most recent phase, phase three.

Previous Work

The scope of the work conducted within the study area has been extensive. As previously discussed, the USACE have been undertaking civil engineering projects in the area since before the turn of the 19th century. Erosion monitoring began in 1946 when a winter storm destroyed U.S. Highway 421. Moreover, by the 1950's, both the state of North Carolina and the county of New Hanover began a series of emergency action, aimed at preserving the remaining structures of the Fort Fisher historic site. Detailed shoreline change surveys predating revetment construction and continuing today monitor the northern most section of the study area (USACE 1967, 1975, 1982, 1994, 1997 – 2005). Investigations by academic institutions began with MOORFIELD (1978) who examined the role of underlying geology and inlet migration on shoreline orientation. SWAIN (1993) examined the effects of inlet closure on Zeke's Island Estuary. Thorough investigations of the underlying geologic framework and its influence on the adjacent shoreline have been conducted by Riggs *et al*. (1995), Cleary *et al*. (1996) and Marcy (1997).

Although numerous investigations have been conducted within the study area, the scope and depth have not been sufficient enough to draw a solid connection between backbarrier modification, and its relative influence on inlet morphology and shoreline change.

Overall, the study site poses a variety of challenges. The variability of the major morphodynamic processes active, in combination with the coastal engineering activities within the study area, provide a unique opportunity to study the influence of inlet migration and closure on shoreline stability. The construction and evolution of an artificial basin, the transition of an inlet system from a single, large stable inlet to small, multiple unstable inlets; all have a distinctive and dramatic impact on shoreline stability and barrier spit growth. Investigating the mechanisms of the shoreline change experienced within the study site will provide valuable insight into determining the relative influence of various environmental controls and help to dictate better local management policy.

OBJECTIVES

This study proposed to investigate the impact of inlet migration and closure on shoreline change within the study area. The primary goal was to quantify shoreline changes through the collection of historical shoreline data and delineate both spatial and temporal trends of shoreline change. In addition, this study attempted to establish relationships between shoreline morphology and inlet behavior.

To accomplish these goals, morphological changes in New Inlet and changes in the nature of the backbarrier environment were quantified and then analyzed both spatially and temporally to establish a link between backbarrier changes, inlet behavior and shoreline morphology.

Although previous investigations within the study site tried to quantify shoreline change, few had the accuracy afforded by recent technological advances of geographic information systems (GIS) and digital shoreline mapping programs. In addition, there have been no investigations into the resultant shoreline changes associated with the closure of New Inlet. This investigation has attempted to establish a link between changes in the behavior of the New Inlet system, including backbarrier modifications, and the shoreline morphology of the Federal Beach barrier spit.

METHODOLOGY

This investigation was based on data derived from various remote sensing sources. Near vertical aerial photographs, othorphotographs, and National Ocean Service (NOS) T-sheets from various years were obtained from local and state archives. These sources include the United States Army Corps of Engineers (USACE), North Carolina Division of Coastal Management (NCDCM), New Hanover County Department of Geographic Information Systems, and Brunswick County Department of Geographic Information Systems.

Remote sensing data coverage of the study area spans over 200 years. The first historical map was produced in 1733 by MOSELEY (Figure 4). Historic charts from the U.S. Coast and Geodetic Survey from the years 1866 and 1889 were used to qualitatively asses the historic nature of the area and establish a conceptual idea of early inlet location and behavior. Contemporary changes, those occurring in the twentieth and twenty first centuries, were quantified by analyzing 20 sets of aerial photographs from 1938 to 2005. The shoreline, though strictly defined as the intersection of water and land surfaces, for practical purposes, is a dynamic boundary, and its dependence on the temporal and spatial scale at which it is being considered often results in the use of a range of different shoreline indicators (BOAK and TURNER, 2005). In this study, 9 km shoreline was identified and digitized following the methodology of such investigators as, DOLAN *et al*. (1978, 1980, 1991); JACKSON (2004) and PAJAK and LEATHERMAN (2002); as the high-water line (HWL). In this investigation the HWL was visually determined as a change in tone left by the maximum runup from a preceding high tide (ANDERS and BYRNES, 1991; CROWELL, LEATHERMAN, and BUCKLEY, 1991; SMITH and ZARILLO, 1990)

T-Sheets

The oldest reliable source of shoreline data in the United States is the National Ocean Service, formally known as the US Coast and Geodetic Survey, T-sheets, which date back to the early to mid-1800s (MORTON, 1991). These maps are constructed from plane-table surveys based on the high-water line and not the mean high water line as reported on the maps (SHALOWITZ, 1964). NOS T-sheets were digitized using a Calcomp™ digitizing tablet and ArcView™ GIS v.3.2a software. Once the map was registered the HWL was digitized into an ArcView polyline shapefile and attributed (JACKSON, 2004).

Aerial Photographs

Aerial Photographs were selected from various archives based on scale, clarity, presence of coastal features and temporal proximity to storm events. Photographs were scanned using an EPSON Perfection ® 1650 scanner. To produce a consistent ground pixel distance of approximately 3 ft. per pixel, scanning resolutions were calculated for each set, and varied from 300 to 600 dpi. Data loss during photo georectification may be minimized if the resolution of the scanned photo and the georeferenced base layer are similar.

After scanning the original hard copy photo to create a digital file, polynomial georectification was performed in three steps: (i) matching of ground-control points (GCPs) on the scanned photo image and base layer, (ii) transformation of the GCP coordinates on the scanned image from a generic raster set to a geographical projection and coordinate system, and (iii) pixel resampling (HUGHES *et al*., 2006). In this investigation the photographs were digitally rectified in ESRI® ArcMap™ 9.1 using the georeferencing tool. Georeferenced photographs were saved as TIFF files. These files were used to create a photo mosaic for each set of photographs. ArcMap™ 9.1 was then used to digitize the visible wet/dry line (HWL), the main ebb channel, associated inlet sand bodies, and subaerial back barrier features.

Measurement of Shoreline and Inlet Related Changes

Standard industry methods for calculating shoreline change and rate statistics have yet to be adopted by the government, public and private sectors. However several calculation methods, such as the endpoint rate (EPR) and “least-squares fit” linear regression rate (LRR) calculation (Table 1), have been intergraded into a computational extension created for ArcView™ called SCARPS (Simple Change Analysis of Retreating and Prograding Systems). This investigation used SCARPS, programmed by JACKSON (2004), as the primary method of calculating shoreline position changes and rates.

All digital shoreline files were projected to North Carolina state plane projection, NAD 1983 datum, GRS 1980 spheroid, and feet map units prior to analysis. Shoreline change was calculated by measuring the position differences of the HWL between each historical shoreline within the GIS. For each analysis, shoreline change transects were cast shore-normal from a baseline and spaced at 457.2 m (1,500 ft.) intervals. Shoreline rate-of-change models and statistics were computed using SCARPS, which include the calculation methods summarized in Table 1. A detailed explanation of each shoreline change calculation is discussed in JACKSON (2004).

The EPR and LRR calculations, widely used by state and local agencies (National Research Council, 1990), were the primary models used to estimate both long-term and short-term shoreline change rates for the current study. Even though shoreline change is not necessarily a linear process, especially adjacent to inlets, these models provide the best approximation of annual change rates (CROWELL *et al*., 1991).

This study discusses the hydraulic nature of the New Inlet systems using the industry standard term “tidal prism”. Tidal prism, as defined by JARRETT (1976) for all inlets along the North Atlantic shoreline, is show by the empirical formula:

$$A=7.75 \times 10^{-6} P^{1.05} \qquad (1)$$

Table 1. Summary of Shoreline Change Calculations

Calculation	Advantage	Diasadvantage	GIS Proceedure	Reference
end-point rate (EPR)	requires only two shorelines; summation of all shoreline influences	neglects data between oldest and youngest shoreline	SCARPS	JACKSON, 2004
linear regression rate (LRR)	utilizes all shoreline data, widely accepted computational method	affected by outliers; tends to underestimate rates	SCARPS	JACKSON, 2004
average of end-point rates (AER)	provides comparable long-term rates to EPR and LRR	tends to overestimate short-term rates	SCARPS	JACKSON, 2004
standard devation of changes (SDC)	provides a measure of shoreline position fluctuation; incorporates shoreline change measured between each data point to the oldest shoreline in the dataset	does not provide a rate calculation	SCARPS	JACKSON, 2004
average zone change (AZC)	summarizes the average shoreline change along a shoreline segment; aids in characterizing shoreline response to various influences	dependent on subjective interpretation of zone location; the location of a zone might move over time	manual	JACKSON, 2004
average zone rates (AZR)	determines average shoreline change rates along a shoreline segment; assigns a single rate to an entire shoreline segment	dependent on subjective interpretation of zone location; the location of a zone might move over time	manual	JACKSON, 2004

Where *P* equals tidal prism and *A* equals the cross sectional area of the inlet. The cross sectional area is measured below mean sea level along the narrowest section of the inlet throat, also know as the inlet minimum width (IMW) (JARRETT, 1976). This investigation however, does not discuss the tidal prism of the New Inlet systems as defined by JARRETT (1976). Due to the constraints of the data set, this study was unable to calculate tidal prism values, nor was it able to acquire field measured tidal prism data.

Generally, inlet tidal prism is a function of bay size, tidal range and frictional factors within the conveyance channels (FITZGERALD *et al.*, 2005). Investigations by FITZGERALD and PENDLETON (2002) into the morphodynamics of New Inlet, Massachusetts, indicate that the migration of tidal channels within the backbarrier control the tidal prism and ultimately the stability of the inlet system Along the west coast of Florida DAVIS AND BERNARD (2003) have shown that anthropogenic modifications of backbarrier bays, including the construction of artificial tidal divides, reduced the tidal prism at some inlets, resulting in instability or closure. Examples include Blind Pass and Dunedin Pass. In addition investigations within Onslow Bay by FREEMAN (2001), KNIERIM (2004), and WELSH (2004) all show a strong correlation between tidal prism magnitude and cross-sectional area, which is consistently found to be reflected in the minimum width of the inlet system. CLEARY and FITZGERALD (2003) have also found that a reduction in the size of a tidal inlet system was the product of a diminished tidal prism.

Moreover, FITZGERALD *et al.*, (2001) noted that a decrease in the depth of an inlet channel increased the propensity of the inlet to migrate. Therefore, this study assumed that as the migration rate of an inlet increases, the depth of the inlet channel decreases.

Additionally, this study assumed that the cross-sectional area of the inlet had diminished if an increase in the migration rate of the inlet occurred, indicating a decrease in the depth of the channel, coincided with a decrease in the IMW.

Prior work within the study area by SWAIN (1993), where empirically derived tidal prism values were evaluated, has shown that significant changes in inlet morphology and behavior, shoreline morphology, and estuarine sedimentation occurred solely from a reduction in tidal prism. Accordingly, this study has employed a number of morphological indicators as natural proxies for field measured or empirically derived tidal prism data.

Morphological changes associated with the New Inlet system, including migration rate, IMW and channel orientation, were evaluated using on screen measurements based on shore normal transects spaced at 6.1 m (20 ft.) intervals. Inlet position was then defined as the exact midpoint along the inlet minimum width. Based upon on screen evaluations the Federal Beach backbarrier area was classified as either backbarrier bay, subaerial marsh or convenience / tidal channels. Changes occurring within the backbarrier, such as variations in bay and subaerial marsh area, were evaluated using SCARPS. Shoaling within the tidal channels was qualitatively evaluated on screen.

The on screen measurements of inlet channel length, width and bay size were compared to produce qualitative tidal prism values. Tidal prism values herein are not discussed in numerical terms but are qualitatively referred to as either “large” or “small”.

Shoreline Position Error

The advent of the personal computer and the subsequent development of high-tech mapping software have allowed for unprecedented accuracy in assessing contemporary shoreline position. Current mapping methods, however improved from traditional mapping techniques, continue to have inherent error. Error in shoreline position can be derived from several sources.

First, error can be introduced before rectification and analysis take place. The acquisition, or image capture, of aerial photographs is in itself is a scientific pursuit, with the challenge of balancing many physical variables. Common distortions include radial distortion, relief distortion, tilt and pitch of the aircraft, and scale variations caused by changes in altitude along a flight line (ANDERS and BYRNES, 1991; CROWELL, LEATHERMAN, and BUCKLEY, 1991; MOORE, 2000; THIELER and DANFORTH, 1994).

Commonly, the HWL is visually determined as a change in tone left by the maximum runup from a preceding high tide (ANDERS and BYRNES, 1991; CROWELL, LEATHERMAN, and BUCKLEY, 1991; SMITH and ZARILLO, 1990). Natural variation in the HWL can derive from cyclic changes in physical environmental forces. An individual HWL has no reference to a tidal datum or a fixed elevation; instead, it may represent a combination of a number of factors, including preexisting beach face morphology, atmospheric (weather) conditions, and the prevailing hydrodynamic conditions such as moon phase and tidal cycle. All of these variables introduce site-specific error associated with the delineation of the HWL.

When assessing the error associated with the polynomial georectification of scanned images, the root-mean-squared error (RMSE) equation is calculated by comparing predicted points from a registered map or aerial photo against the actual points referenced on a highly controlled base map or orthophoto. Error reduction and quality control of digitized aerial photography were accomplished by recalculation of RMSE values from randomly selected points across registered aerial photographs using the 2002 orthophotos as a standard. During the georeferencing process, a target RMSE value of less than 9 ft was sought per photo and was easily obtained from higher quality controlled imagery. Older imagery from the 1930s to 1960s generally contained more distortion and produced higher RMSE values because of stretching, shrinking, and warping of the photographic paper or medium. Unfortunately, due to limited technology, NOS T-Sheets often contain elevated RMSE values (ANDERS and BYRNES, 1991). Table 2 provides a summary of worst-case shoreline position errors associated with various shoreline data sources.

Delineation of Shoreline Reaches

When examining long-term changes along large tracts of shoreline, both temporal and spatial variations in the morphological changes can be expected. The influence of the many dynamic environmental factors, as previously mentioned, is highly variable within study area. Identifying and delineating zones along the barrier spit based on common behavioral trends is critical to better understanding the evolution of the barrier's shoreline in response to various influences, both natural and anthropogenic.

The current study identified two "Shoreline Change Zones" (SCZ) (Figure 7). A shoreline change zone was defined as a segment of the shoreline displaying an overall difference in magnitude of erosion or accretion from adjacent reaches due to one primary

Table 2. Summary of estimated worst-case shoreline position error

Potential Error Source	Scale	Error (m)	Reference
		HWL Displacement	
medium-sized sand beach with a slope 3° to 6° (Atlantic Coast)	1:1	7	DOLAN et al., 1980
storms (Atlantic Coast)	1:1	30	MOORE, 2000
		Maps and Aerial Photography	
NOS T-sheets (1844-1880)	1:10000	9	CROWELL et al., 1991
NOS T-sheets (1880-1930)	1:10000	8.5	CROWELL et al., 1991
aerial photography	1:10000	7.5	CROWELL et al., 1991
		Shoreline Position Measurement	
digitizer error	1:10000	5	ANDERS and BYRNES, 1991
operator error	1:10000	2.5	CROWELL et al., 1991

influencing factor, such as an inlet, or combination of factors (JACKSON, 2004). Delineation of shoreline change zones was based upon quantitative long-term erosional and accretional trends, coupled with an analysis of the rate-of-change statistics, standard deviation of shoreline position change and a cursory examination of the GIS aerial photo set.

In addition to SCZs, this study identified four “Inlet Migration Zones” (IMZ) (Figure 7). An inlet migration zone is defined as a segment of the shoreline displaying an overall difference in magnitude of migration rate from adjacent reaches due to one primary influencing factor, such as backbarrier geometry, or combination of factors. Inlet migration zones were identified both qualitatively and quantitatively. Visual identification of the minimum width of the system was coupled with an analysis of the inlet migration rate, as evaluated using the EPR calculation method, in order to delineate shoreline segments into zones.

RESULTS

This study focused on both the morphological changes of the New Inlet system, and how these changes have impacted the planform evolution of the Federal Beach barrier spit. This investigation examined the changes occurring during the past century, specifically from 1938 to 2005. However, the changes occurring along the Federal Beach barrier spit, and the morphological changes of the New Inlet system, are reported here separately. All shoreline change and inlet migration values reported below, unless otherwise noted, are derived from the EPR calculation method. Additionally, the term “average” is used to refer to the arithmetic mean.

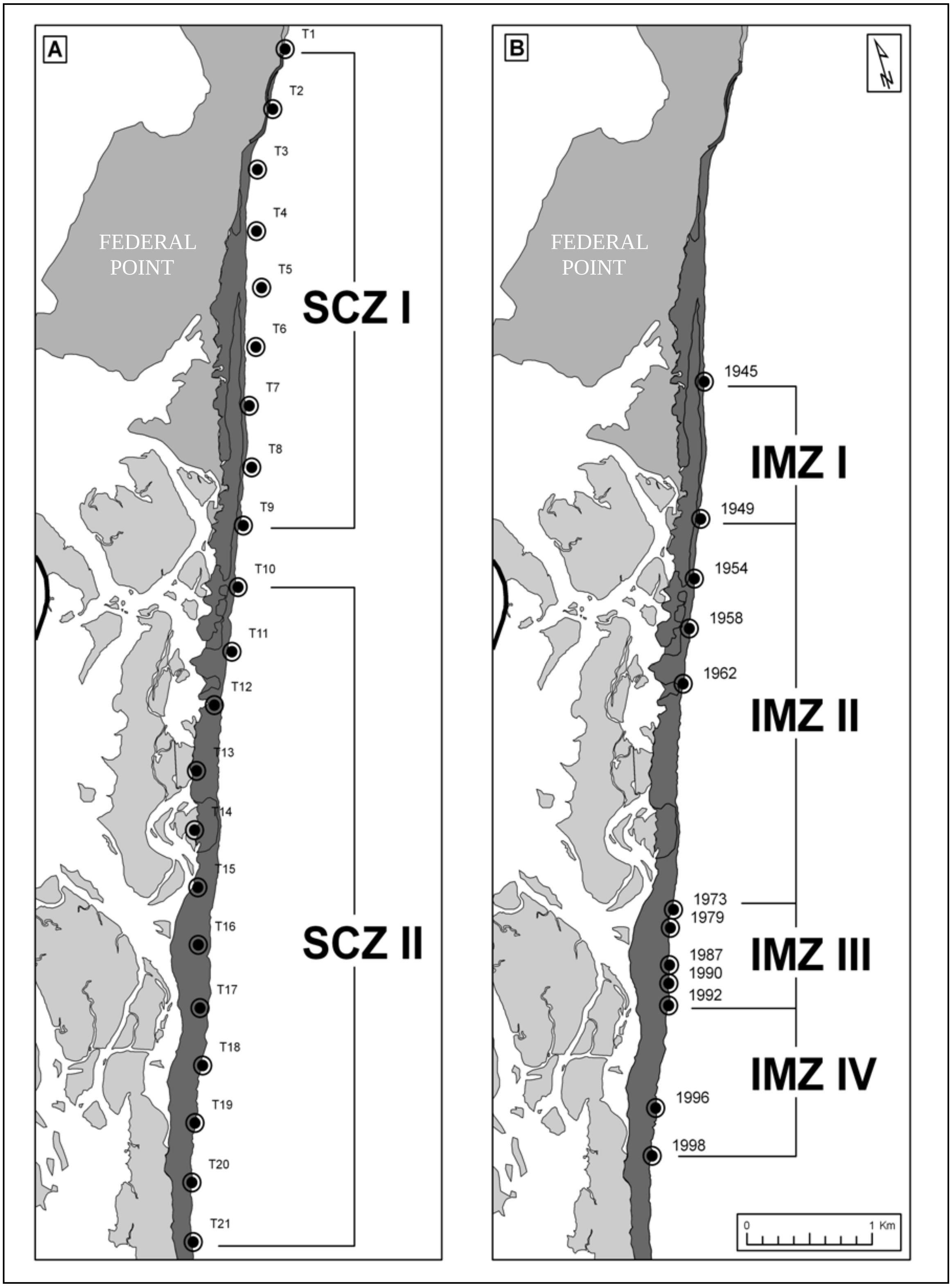


Figure 7. (a) Location of Shoreline Change Zones (SCZ) and their respective transects for Federal Beach's shoreline configuration as of 2003. (b) Location of Inlet Migration Zones (IMZ) and the location of New Inlet B for the years 1945 to 1998.

Inlet Changes

The Federal Beach barrier spit and associated inlet systems are dynamic and complex. There is a significant anthropogenic influence, both spatially and temporally, on the behavior and nature of the New Inlet system. The Rocks, since construction in 1887, has been the major factor influencing the morphodynamic evolution of the area (SWAIN, 1993). By vastly changing the hydraulic nature of New Inlet, The Rocks initiated the collapse and migration of the large and stable New Inlet system. This in turn has led to the development of a multiple inlet system. The scope of this study, from the years 1938 to 2005, will include two such migrating inlet systems. The first inlet herein referred to as New Inlet A, opened previous to 1938, between 1887 and 1895, and closed between 1956 and 1959. The second, herein referred to as New Inlet B, opened between 1938 and 1945 and closed in 1999.

New Inlet A

Between 1887 and 1895 Federal Beach was breached near the point of spit attachment, forming New Inlet A. By 1912 New Inlet A had migrated approximately 5 km to the south (SWAIN, 1993). The first geographically referenced inlet location used in this study was the 1938 position of New Inlet A, approximately 6.5 km south of the Fort Fisher Historic Site (Figure 8). This location was used as the baseline for all New Inlet A migration measurements. The geographically referenced New Inlet A data set used in this study spans from 1938 to 1954. Over the course of this period New Inlet A migrated south a net distance of 384 m at an average rate of 47 m/yr, and the inlet minimum width changed from 818 m (1938) to 2200 m (1954). New Inlet A minimum widths and migration rates are summarized in Table 3.

New Inlet A from 1938 to 1945 migrated 213 m to the south averaging 30 m/yr. From 1945 to 1949 New Inlet A migrated south 320 m at a much faster rate, 80 m/yr. From 1949 to the last georectified position in 1954, New Inlet A migrated 150 m to the north (Figure 8). The apparent reversal in the migration direction of the New Inlet A system can be attributed to an expansion in the size of the inlet channel, 174 m (1949) to 347 m (1954), due to Hurricane Hazel, rather than a true migration of the system. This apparent migration is caused by the analytical methodology used in this investigation to measure inlet position, as previously described.

This investigation is unable to determine the exact location and year of New Inlet A's closure due to the unavailability of georectified photography from 1954 to 1962. However, based on non-rectified imagery it can be concluded that the New Inlet A system closed between 1956 and 1959, 1 km south of its 1938 position and approximately 7.4 km south of the Fort Fisher Historic Site.

New Inlet B

The Federal Beach barrier spit was breached between 1938 and 1945, forming New Inlet B. Again, due to the lack of aerial imagery during this period the exact date of spit breaching is not known. However, the 1945 position of New Inlet B, approximately 1 km south of the point of spit attachment, suggested that New Inlet B opened within the previous 2 years (Figure 9). Moreover, upon examining the history of tropical and extra-tropical storms affecting the area, only two storms from 1939 to 1944 have had the

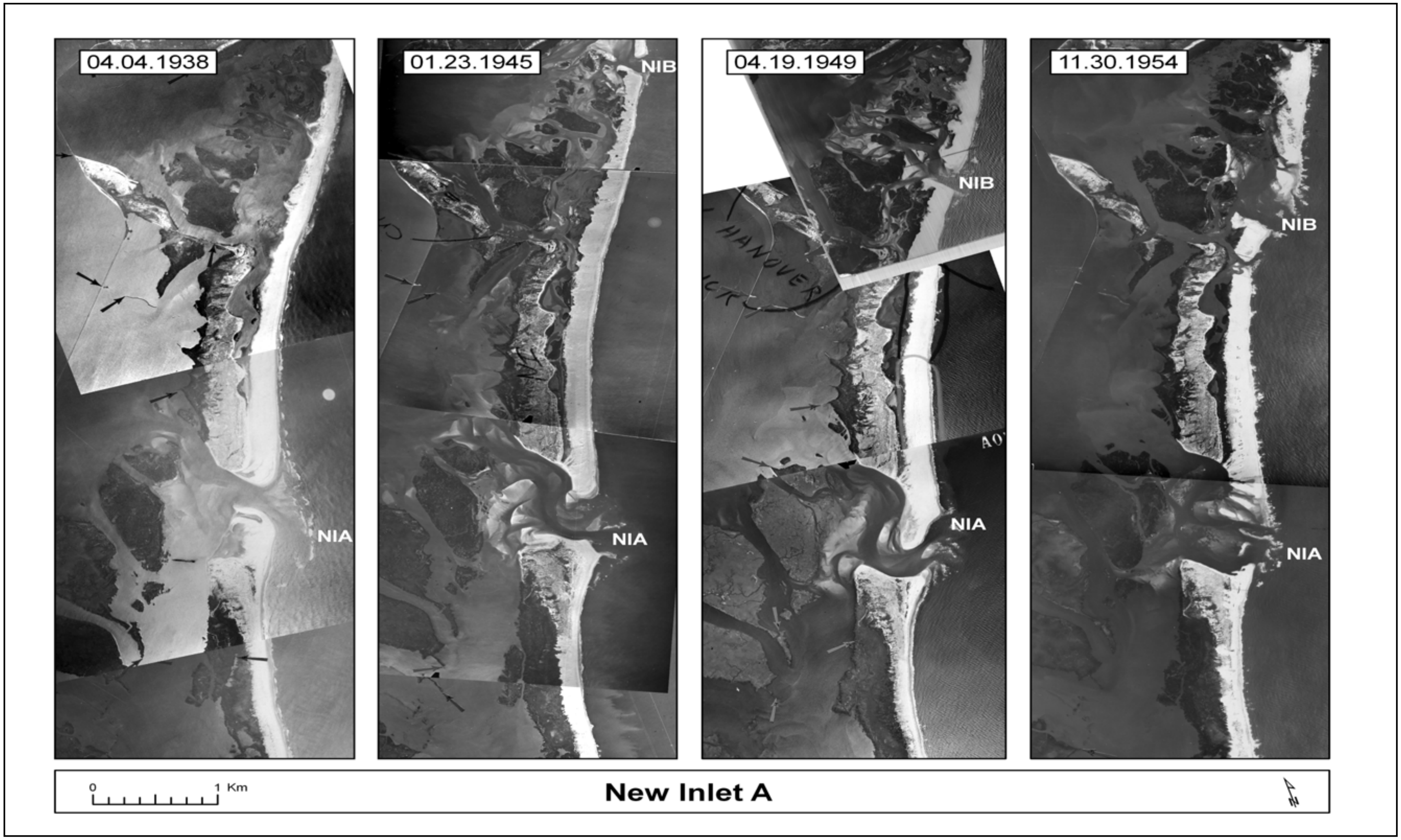


Figure 8. Migration of New Inlet A (NIA) along the Federal Beach barrier spit from 1938 to 1954

Table 3: Summary of New Inlet A Migration Rates and Inlet Minimum Width Values

New Inlet A

Date	Inlet Minimum Width *
1938	249
1945	450
1949	297
1954	671

Average IMW: 417

Average Migration Rate: 47

Era	Range (mo)	Distance *	Migration Rate **
1938 -1945	69	213	30
1945 -1949	51	323	81
1949 -1954	67	152	30
1938 - 1954	187	689	44

* meter
** meter/year

potential to significantly impact Federal Beach, both of which occurred during 1944. One storm specifically, The Great Atlantic Hurricane (9/14/1944), is suspected as the cause of the initial barrier spit breach that resulted in the formation of New Inlet B. This investigation will therefore assume that the initial opening of New Inlet B occurred on September 14, 1944. However, the 1945 aerial imagery was used to establish the first geographically referenced location of New Inlet B. This location, approximately 2.5 km south of the Fort Fisher Historic Site, was used as the baseline for all New Inlet B migration measurements, summarized in Table 4.

The slowest migration rates occurred from 1987 to 1990, when New Inlet B migrated only 6 m/yr (Figure 10). The maximum annual migration rate occurred from 1945 to 1949, with New Inlet B migrating 248 m/yr (Figure 9). From the initial opening in 1944 to the closure of the inlet in 1998, New Inlet B migrated south a total of 6 km, at a mean rate of 106 m/yr. The average IMW value from 1945 to 1998 was 204 m. Seasonal, as well as geographic variations in the environmental factors influencing the New Inlet system resulted in a relatively large standard deviation in migration rate and IMW, 74 and 115 respectively. The large variation about the mean of these data sets indicates a relatively unstable system.

Inlet Migration Zones

Inspection of the New Inlet B data set suggests that the Federal Beach barrier spit can be subdivided into zones based on inlet behavior, specifically migration rate. By comparing the migration rates of the New Inlet B system, four "Inlet Migration Zones" (IMZ) were delineated. Migration rates were influenced by the location of the inlet along

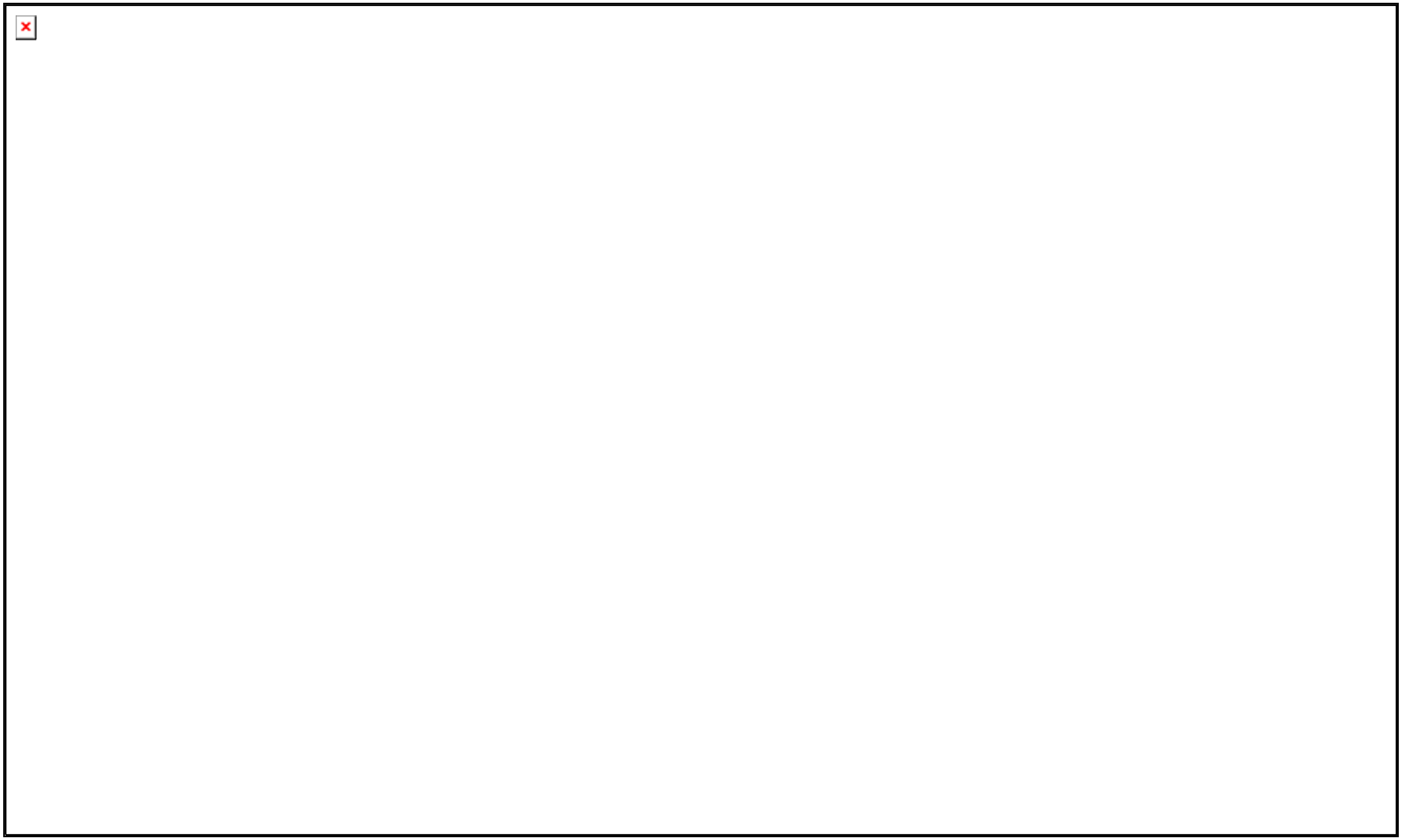


Figure 9. Migration of New Inlet B (NIB) along the Federal Beach barrier spit from 1945 to 1976.

Table 4: Summary of New Inlet B Migration Rates and Inlet Minimum Width Values

New Inlet B

Year	Inlet Minimum Width*	Zone	Average IMW*
1945	131		
1949	174	IMZ I	152
1954	347		
1958	219		
1962	274	IMZII	217
1973	68		
1976	335		
1979	291		
1987	196	IMZ III	241
1990	280		
1992	274		
1996	50	IMZ IV	118
1998	30		

Era	Range (mo)	Distance*	Migration Rate**	Zone	Distance	Migration Rate
1945 -1949	51	1049	247	IMZ I	1049	247
1949 -1954	67	469	84			
1954 -1958	41	378	111			
1958 -1962	46	390	102	IMZ II	3060	113
1962 -1973	141	1823	155			
1973 -1976	31	146	57			
1976 -1979	41	140	41			
1979 -1987	86	506	71	IMZ III	963	52
1987 -1990	39	18	6			
1990 -1992	21	152	87			
1992 -1996	55	799	174	IMZ IV	1170	211
1996 -1998	18	372	248			
1945-1998	637	6242	118			

* meter
** meter/year

Figure 10. Migration of New Inlet B (NIB) along the Federal Beach barrier spit from 1979 to 1999.

the barrier spit with zone delineation corresponding to spatial variations in the systems' physical setting with respect to the geometry of the backbarrier basin. Inlet migration rates and IMW values for each of the four IMZ are shown in Table 4. The northern and southern most zones (IMZ I and IV) were identified as areas of accelerated inlet migration. The two middle zones (IMZ II and III) were identified as areas of decreased instability, and exhibited migration rates that were less than IMZ I and IMZ IV.

Due to the lack of aerial photographs pre-dating 1938 Inlet Migration Zone delineation for the New Inlet A data set was not conducted by this investigation.

Inlet Migration Zone I

New Inlet B occupied IMZ I during the years 1945 to 1949 (Figure 7 and Figure 9). As previously stated, this era can be described as a period of inlet re-equilibration. The system migrated 1049 m to the south and, it is assumed, began capturing an increasing amount of the overall tidal exchange, increasingly becoming the dominate inlet. Moreover, during this period the IMW increased from 131 m to 174 m, indicating inlet growth and suggesting an increase in stability.

Inlet Migration Zone II

Inlet migration zone II is defined by the position of New Inlet B along the Federal Beach barrier from the years 1949 to 1973 (Figure 7 and Figure 9). In this zone the New Inlet system continued to migrate south. Migration rates for IMZ II ranged from a maximum rate of 155 m/yr (1962-1973), to a minimum migration rate of 84 m/yr (1949-1954). The average rate for this era was 113 m/yr.

The overall maximum IMW of the New Inlet B system, 347 m, occurred in 1954; approximately one week after a major class 3 hurricane, Hazel, passed through the area. Increased shoaling of the inlet throat by 1973 reduced the width of the system to a zone wide minimum of 68m. The average inlet minimum width for IMZ II was 217 m.

Throughout the study area changes in inlet width were found to be consistent with changes in inlet migration rates. The data from this investigation suggests a weak, apparent inverse relationship between the two physical parameters. This relationship is highlighted by observing the changes in the IMW and migration rate values between 1962 and 1973. As the migration rate of the inlet increases from 102 m/yr (1958- 1962) to 155 m/yr, the IMW value decreases from 274 m (1962) to 68 m (1973). In addition, evidence of this inverse relationship can be found by examining the IMW values and migration rates from 1973 to 1976. The IMW of New Inlet B grows from 68 m (1973) to 335 m (1976) and migration rate decreases to an average of 57 m/yr. Moreover, the relationship between these two inlet parameters can further be determined by comparing the average IMW and migration rate values of IMZ II to IMZ III and IMZ IV (Table 4).

Inlet Migration Zone III

From 1973 to 1992 New Inlet B occupied IMZ III (Figure 7 and Figure 10). The maximum migration rate for IMZ III, 87 m/yr (1990-1992), and the minimum migration rate, 6 m/yr (1987-1990) occur in consecutive survey periods and mark the southern boundary of IMZ III. The northern boundary of IMZ III is marked by the minimum IWM, 68 m (1973), and by the maximum IMW 335 m (1976). There is a decrease in the instability of New Inlet B along Zone III, as indicated by the low average migration rates and large IMW. IMZ III has the highest IMW values and the lowest migration rates of all the zones. The average IMW was 275 m and the average migration rate was 37 m/yr. Again, this illustrates the partial link between the two inlet parameters, IMW and migration rate. This is not a strict linear relationship however; this still suggests that the rate of inlet movement and the resultant morphology of the Federal Beach barrier is a function of several factors, including the position of the inlet with respect to the geometry of the backbarrier basin.

Inlet Migration Zone IV

This zone is characterized by the closure of the New Inlet B system (Figure 7 and Figure 10). Similarly to when New Inlet B was located along IMZ I, the New Inlet B system in IMZ IV was a comparatively small, rapidly migrating system. The average inlet migration rate within IMZ IV is 211 m/yr, and the average IMW is 40 m. From 1992 to 1998 New Inlet B migrated a net distance of 1.2 km. At this juncture it appears that the hydraulic inefficiency of the channel begins to cause the inlet throat to shoal thus initiating the closure of the system. By March 19, 1999 the system is completely closed. Based on the non-rectified aerial imagery of New Inlet A, it appears that the New Inlet B system closes in approximately the same location, suggesting that the same environmental variables that triggered the closure of New Inlet A may have had a similar impact on New Inlet B.

Shoreline Change

The shoreline, though previously defined as simply the intersection of the water and land surfaces, is a dynamic and highly variable boundary. The morphology of any given shoreline is the result of the interactions between the many physical forcing mechanisms and the environmental variables of the area. The many factors influencing coastal morphology work in concert on varying spatial and temporal scales. As discussed in CAMFIELD and MORANG (1996), at least 10 years of continuous shoreline data are needed to interpret short-term trends and a minimum of 50 years of data are needed to identify long-term trends. Barring the availability of such an extensive and continuous short-term data set, this investigation seeks to identify long-term shoreline change as it is influenced by inlet migration and closure.

The focus of this study's investigation on the shoreline changes occurring along the Federal Beach barrier varied in scope. First, total barrier spit, or "net" changes were evaluated. Secondly, zone wide changes were examined. This study identified two Shoreline Change Zones, SCZ I and SCZ II (Figure 7) present along the Federal Beach barrier spit. The changes occurring within the northern zone (SCZ I) are primarily influenced by the absence of an inlet system after 1949, while the southern zone (SCZ II) is characterized as a zone of strong inlet influence. The results from barrier-wide shoreline change analysis, and from zone-wide analysis, are presented in Table 5 and Table 6 respectively.

Barrier-wide Shoreline Change

The earliest georectified images obtained for this study were 1938 aerial photographs. This data set however is incomplete, and the entirety of the study area shoreline was not imaged. Therefore, in the following section the 1945 data set is utilized as the baseline for all shoreline change analysis.

From 1945 to 2005 the Federal Beach barrier spit shoreline accreted approximately 6 m at a rate of 0.1 m/yr (Figure 11 and Table 5). However, along the 21 survey transects, only ten showed positive net change values for the 1945 to 2005 era (Table 5). The average change for the ten prograding transects was 86 m, at a rate of 1.4 m/yr. The maximum amount of accretion occurred along transect 13 and 14 (T13 & T14), with each transect prograding 147 m and 155 m respectively. The least amount of positive shoreline change, 17 m, occurred along T21 (Figure 11).

Additionally over the course of the study period ten transects experienced net erosion. The average erosion along all retrograding transects was 73 m, at a rate of -1.2 m/yr. The greatest amount of shoreline retreat, 137 m, occurred at T4 (Figure 11). The shoreline along the Transect 9 cell experienced the least amount of erosion, with only 19 m of net change. Shoreline change for the 1945 to 2005 era could not be measured at transects 17. In 1945 T17 was located in too close of a proximity to New Inlet A to provide an accurate shoreline position.

Inspection of the data pertaining to the decadal changes along Federal Beach indicates progadation occurred more frequently then periods of erosion, with accretion occurring during four of the six decades surveyed from 1945 to 2005 (Table 5). However,

Table 5: Summary of Shoreline Change by Transect

Era	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15	T16	T17	T18	T19	T20	T21
1945/01/23 to 1954/11/30	10**	1	13	9	13	0*	28	19	0	0	0	-47	-14	27	18	48	0	-13	-2	19	11
1954/11/30 to 1962/03/13	-7	-50	-63	-42	-25	0	-20	-15	0	0	0	106	-22	-82	-75	-123	0	-42	24	29	-34
1962/03/13 to 1973/12/10	-27	19	-18	-35	-39	14	-17	15	41	44	80	96	200	184	97	-71	-90	-66	-17	-21	20
1973/12/10 to 1987/02/08	-23	-6	-47	-36	-27	-43	-24	-28	-27	-32	-25	-6	16	95	149	148	-7	-127	-134	-45	7
1987/02/08 to 1996/09/23	-7	10	0	-37	-43	-36	-33	-13	-22	-8	0	0	-10	-25	-50	70	203	227	4	-71	-88
1996/09/23 to 2005/01/01	-7	-4	-2	4	7	-12	-31	-22	-29	-12	-7	0	-15	-52	-34	-41	-29	-5	164	131	102
1945/01/23 to 1949/04/19	4	-15	-13	-7	2	17	-22	-58	-199	-35	6	14	16	25	48	89	0	-58	-73	-51	-43
1949/04/19 to 1954/11/30	6	16	26	16	11	0	50	77	0	0	0	-61	-30	2	-30	-41	0	45	71	70	54
1954/11/30 to 1958/05/04	-6	-19	-31	-6	9	0	-6	1	0	0	0	-67	-150	-180	-169	-227	0	0	0	0	0
1958/05/04 to 1962/03/13	-1	-31	-31	-36	-35	-40	-14	-16	31	56	340	173	128	98	94	104	114	0	0	0	0
1962/03/13 to 1973/12/10	-27	19	-18	-35	-39	14	-17	15	41	44	80	96	200	184	97	-71	-90	-66	-17	-21	20
1973/12/10 to 1976/07/14	-4	1	5	-4	-5	-17	-9	-9	-15	-22	-9	1	4	-10	0	103	52	42	52	84	89
1976/07/14 to 1979/12/26	-2	-6	-9	-13	-8	-10	-12	-24	-33	-39	-43	-40	-20	49	0	20	47	12	-38	-52	-36
1979/12/26 to 1987/02/08	-17	-1	-42	-19	-14	-16	-3	5	20	30	27	33	31	56	110	24	-107	-180	-148	-77	-46
1987/02/08 to 1990/05/08	2	2	15	-1	1	3	-8	-11	-5	24	26	14	15	8	31	0	-37	4	23	0	-11
1990/05/08 to 1992/02/03	-23	-13	-11	-10	-15	-16	-19	1	-14	-15	-12	-10	-17	-26	-25	0	0	34	-44	-69	-56
1992/02/03 to 1996/09/23	13	21	-4	-26	-28	-23	-5	-3	-3	-17	-14	0	-8	-8	-56	-33	0	188	25	-1	-21
1996/09/23 to 1998/03/13	12	-5	-18	-7	1	10	-12	2	14	-2	0	0	-8	-19	-2	-1	-11	7	145	70	-17
1998/03/13 to 1999/03/19	-11	11	24	12	2	-8	7	-4	-9	-6	-6	-7	3	-12	-4	-3	5	2	33	30	32
1999/03/19 to 2000/04/05	1	-7	-8	-8	-3	1	-5	-10	8	-1	-11	-4	-9	7	16	-2	1	-9	-40	-15	26
2000/04/05 to 2001/03/10	-10	-1	-16	7	-2	-15	-15	-20	-21	-19	5	-2	-7	-23	-36	-34	-27	-20	2	5	26
2001/03/10 to 2002/01/01	-1	-2	14	-17	-13	-12	-11	3	-6	25	8	4	-1	-4	-7	-5	12	13	20	33	25
2002/01/01 to 2005/01/01	1	0	3	17	21	11	4	7	-14	-9	-3	-1	7	-1	-2	3	-9	2	5	10	11
1945/01/23 to 2005/01/01	-61	-30	-117	-137	-115	-86	-96	-42	-19	59	129	132	155	147	105	31	0	-26	40	43	17

* 0 represents a gap in shoreline coverage at the given transect for the given data set

** all shoreline change values are in meters

Table 6: Summary of Shoreline Change and EPR by Shoreline Change Zone

	SHORELINE CHANGE **		SHORELINE CHANGE EPR ***	
	SCZ I	SCZ II	SCZ I	SCZII
Transects	1 to 9	10 to 21	1 to 9	10 to 21
Era				
1945/01/23 to 1954/11/30	10	4	1.1	0.4
1954/11/30 to 1962/03/13	-25	-18	-3.4	-2.5
1962/03/13 to 1973/12/10	-5	38	-0.4	3.2
1973/12/10 to 1987/02/08	-29	3	-2.2	0.2
1987/02/08 to 1996/09/23	-20	21	-2.1	2.2
1996/09/23 to 2005/01/01	-11	17	-2.5	4.0
1945/01/23 to 1949/04/19	-6	-5	-1.5	-1.2
1949/04/19 to 1954/11/30	22	7	4.0	1.2
1954/11/30 to 1958/05/04	-6	-66	-1.9	-19.3
1958/05/04 to 1962/03/13	-19	98	-5.0	24.1
1962/03/13 to 1973/12/10	-6	38	-0.5	3.2
1973/12/10 to 1976/07/14	-6	32	-2.4	12.4
1976/07/14 to 1979/12/26	-13	-12	-3.8	-3.4
1979/12/26 to 1987/02/08	-10	-21	-1.3	-2.9
1987/02/08 to 1990/05/08	0 *	8	0.0	2.5
1990/05/08 to 1992/02/03	-13	-20	-7.6	-11.4
1992/02/03 to 1996/09/23	-6	5	-1.4	1
1996/09/23 to 1998/03/13	0	14	0.0	9.1
1998/03/13 to 1999/03/19	3	6	3.0	5.5
1999/03/19 to 2000/04/05	-4	-3	-4.0	-3.3
2000/04/05 to 2001/03/10	-10	-11	-10.0	-11.9
2001/03/10 to 2002/01/01	-5	10	-5.0	12.2
2002/01/01 to 2005/01/01	6	1	2.0	0.4
1945/01/23 to 2005/01/01	-78	69	-1.3	1.2
Average Zone Change **	-5	5		
Average Zone Rate ***			-2.1	1.1

* represents a gap in shoreline converage at the given transect for the given data set
** all shoreline change values are in meters
*** all rate-of-change values are in meters/year

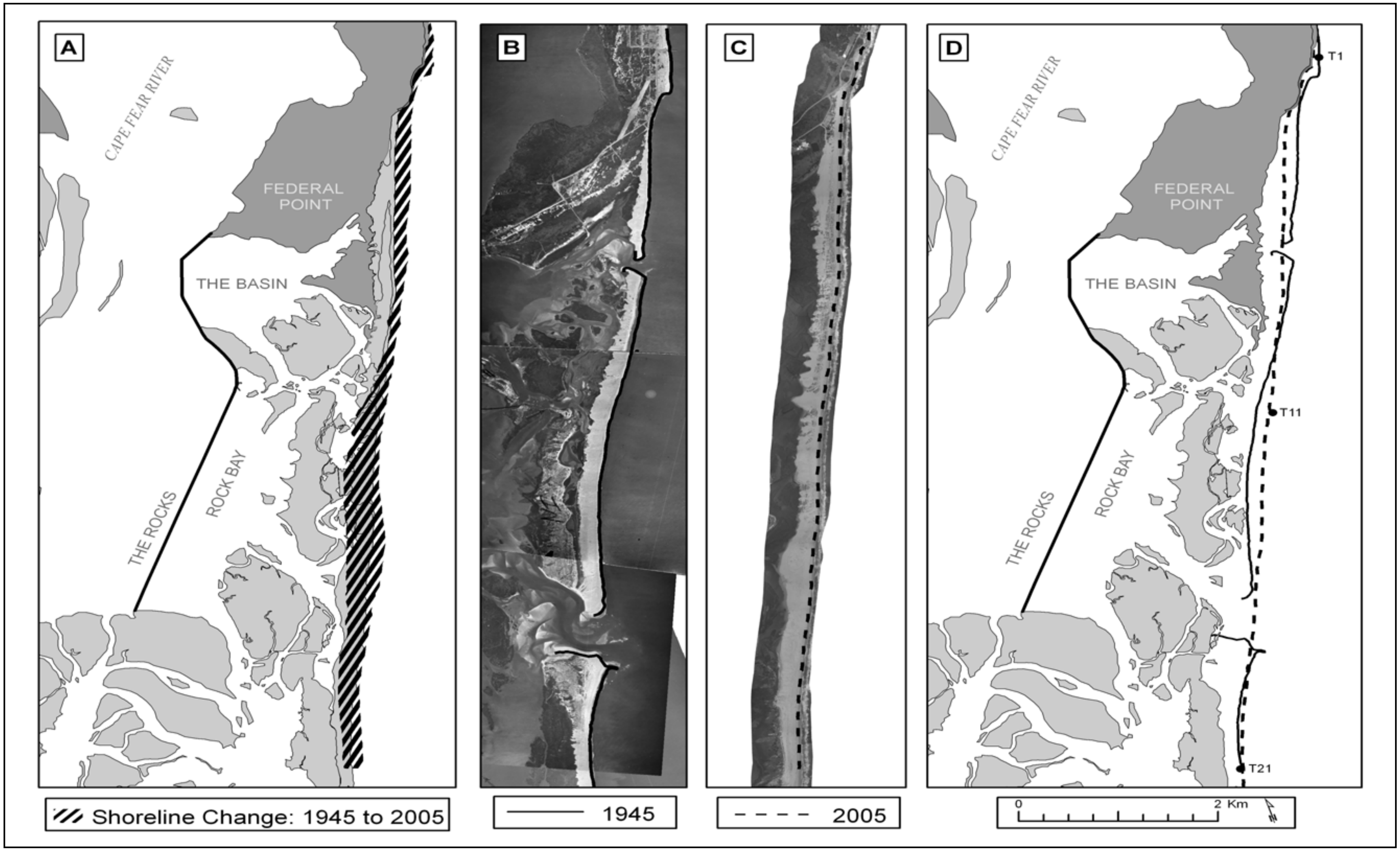


Figure 11. (a) Regions of historical shoreline fluctuation durning the time period (b) 1945 to (c) 2005. (d) Barrier spit shoreline position 01.23.1945 and 01.01.2005.

two of the three decades with the largest magnitude change have been periods characterized by erosion greater then 10 m.

The maximum amount of seaward change, approximately 20 m, occurred during the 1962-1973 survey period (Figure 12). The greatest changes during this period occurred along Transects 11-15, each averaging 132 m of accretion, at a rate of 12 m/yr. The greatest seaward shoreline change, 200 m, occurred along Transect 13. From 1962 to 1973 the average shoreline loss along all eroding transects was 41 m. The most significant erosion occurred along Transect 17, with the shoreline translating 90 m landward.

Federal Beach experienced the most significant losses during the period between 1954 and 1962; with erosion occurring along thirteen of the sixteen transects (Figure 12). Average shoreline retreat per transect was 46 m at a rate of 6 m/yr. However, erosion rates were as high as 123 m/yr (T13). Of the three transects where seaward change occurred, the most significant accretion, 106 m, was along T12. Average change for all prograding transects was 53 m, at a rate of 7 m/yr.

Zone-wide Shoreline Change

To better describe and discuss changes along Federal Beach, the shoreline was subdivided into two separate reaches, SCZ I and SCZ II (Figure 7). Shoreline Change Zones were delineated, as previously described, by a qualitative examination the accretion and erosion trends of the digitized shorelines, coupled with an analysis of the rate-of-change statistics and the standard deviation of shoreline position change (Figure 13).

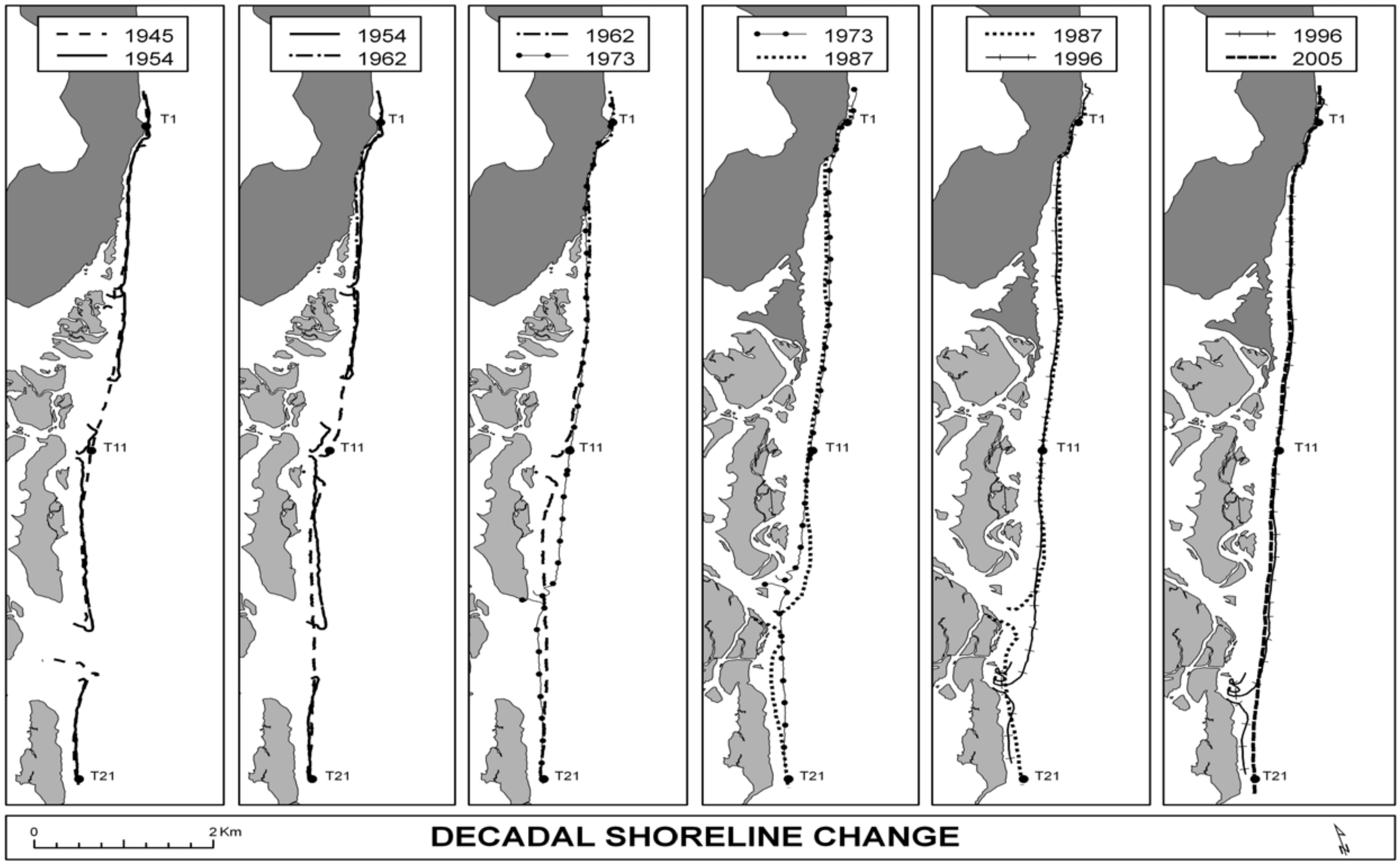


Figure 12. Federal Beach shoreline change by decade or closest interval available from data set.

Shoreline Change Zone I

Shoreline change zone I, located in the northern most portion of the study area, is approximately 3.6 km long. The zone is bound on the north by the Fort Fisher revetment and T1, and bound at the south by T9 (Figure 7).

Shoreline Change Zone I is a retrograding shoreline reach. For each of the 17 periods defined by the photographic coverage, from 1945 to 2005, SCZ I experienced an average net change of -5 m. From 1945 to 2005 the shoreline along each of the nine transects within SCZ I experienced erosion (Figure 11 and Table 6). Net shoreline change along the reach was -78 m at a rate of -1.3 m/yr. The shoreline along transect 4 underwent the most significant changes during this period with the shoreline eroding 137 m. The least amount of erosion, 20 m, occurred along T9.

There are, however, three periods in which net shoreline accretion occurred. The largest net accretion for SCZ I occurred during the period 1949 to 1954 (Figure 14). During this era the shoreline along each transect experienced positive change and the entire zone prograded 22 m, at a rate of 4 m/yr. The most significant accretion, 77 m, occurred along the shoreline at T9. The least seaward movement, 6 m, occurred along T1. The portion of barrier spit within SCZ I prograded during two other eras, 1998-1999 and 2002-2005. The average net shoreline change for these two periods was 4.5 m at a rate of 2.5 m/yr.

The greatest zone-wide erosion occurred from 1958 to 1962 (Figure 14). During this period the net landward movement of the shoreline within SCZ I was -19 m, at a rate of -5 m/yr. The most significant change occurred along T6, which experienced 40 m of

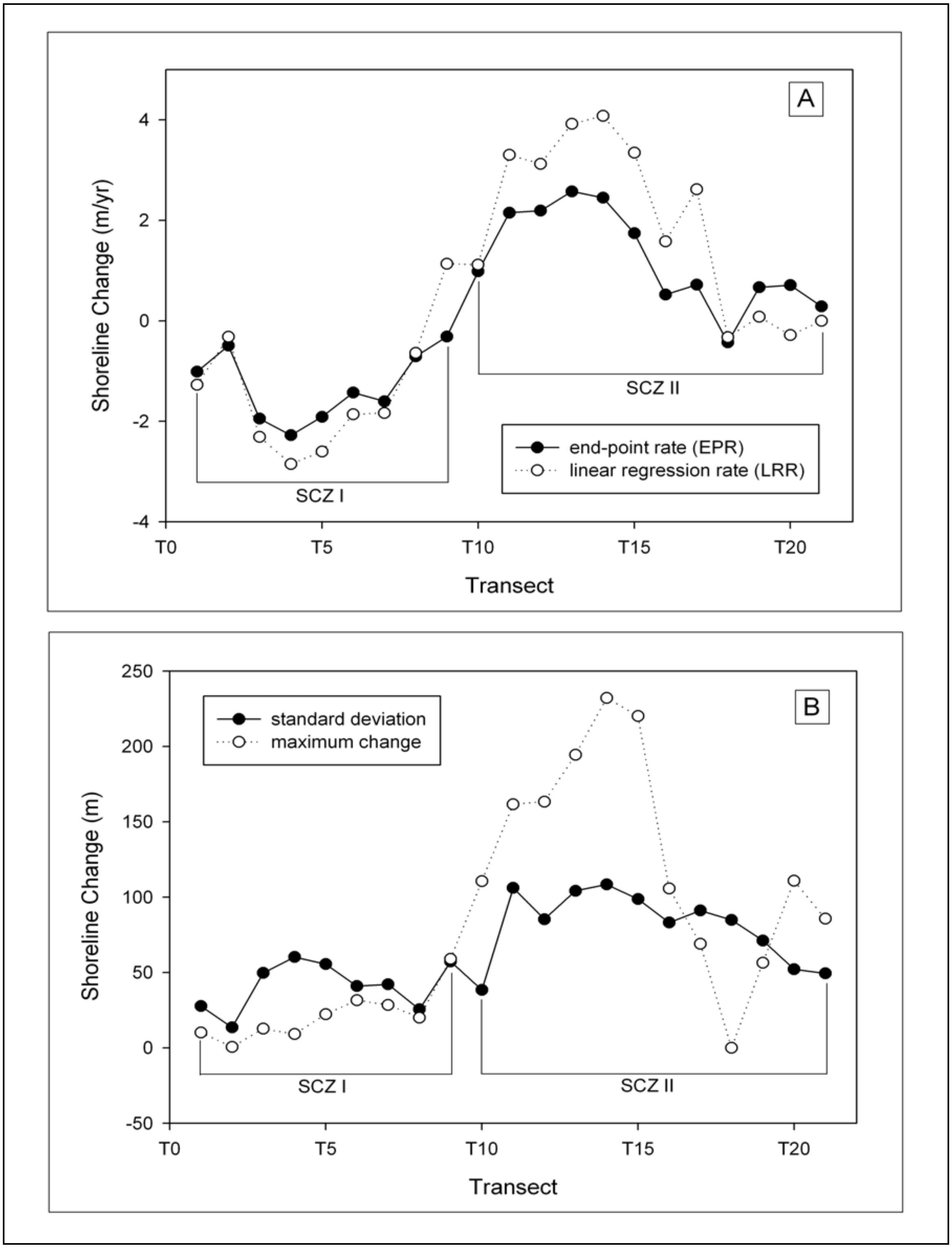
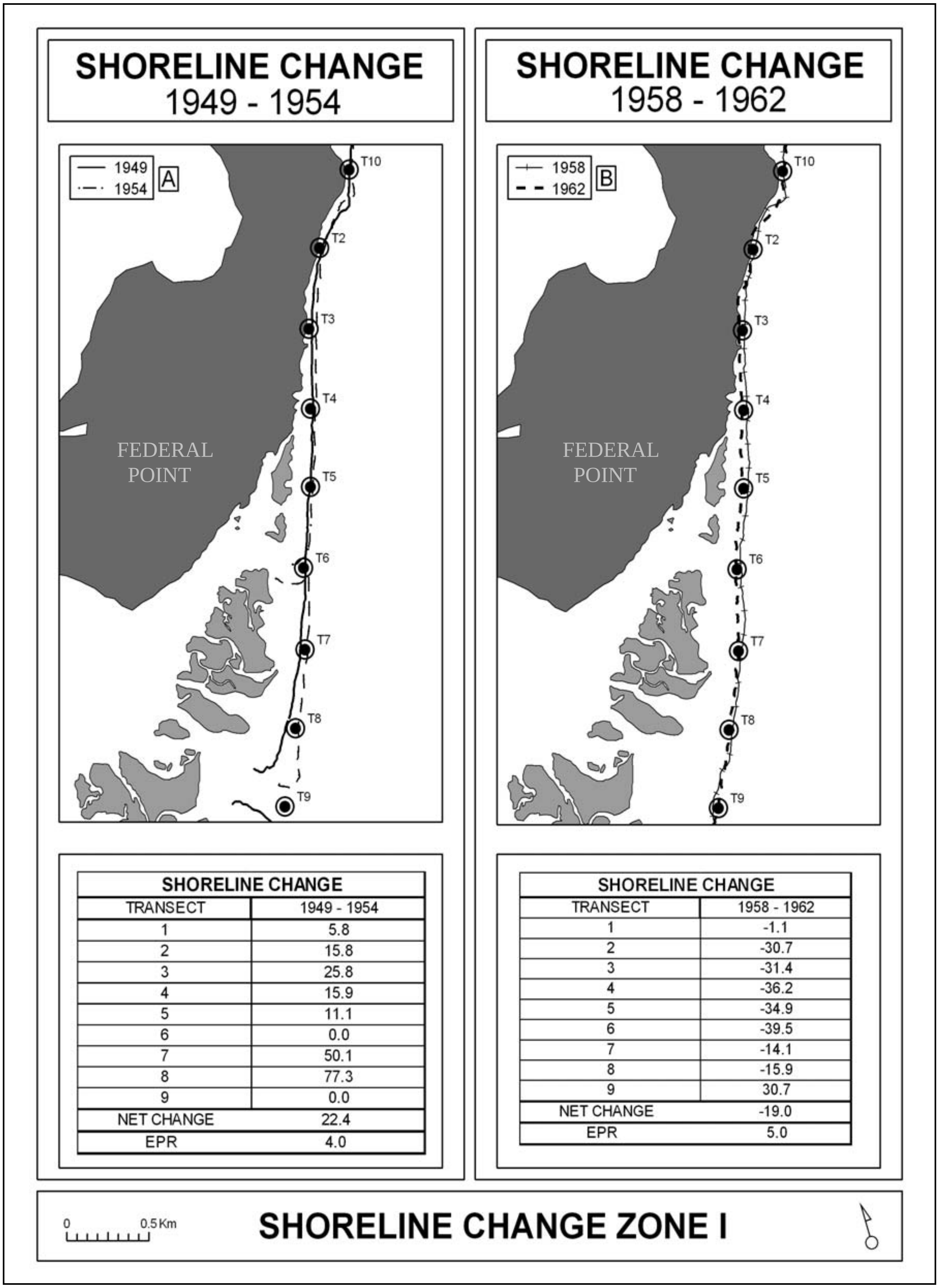


Figure 13. Plot of (a) shoreline rate-of-change statistics and (b) standard deviation and maximum change values, for each transect along Federal Beach from 1938 to 2005.



SHORELINE CHANGE	
TRANSECT	1949 - 1954
1	5.8
2	15.8
3	25.8
4	15.9
5	11.1
6	0.0
7	50.1
8	77.3
9	0.0
NET CHANGE	22.4
EPR	4.0

SHORELINE CHANGE	
TRANSECT	1958 - 1962
1	-1.1
2	-30.7
3	-31.4
4	-36.2
5	-34.9
6	-39.5
7	-14.1
8	-15.9
9	30.7
NET CHANGE	-19.0
EPR	5.0

Figure 14. Shoreline change for SCZ I. (a) The largest net accretion occurred during the 1949-1954 survey period. (b) The largest net erosion occurred during the 1958-1962 survey period.

erosion at a rate of 10 m/yr. The smallest significant change, -14 m, occurred along T7 at a rate of -3.7 m/yr.

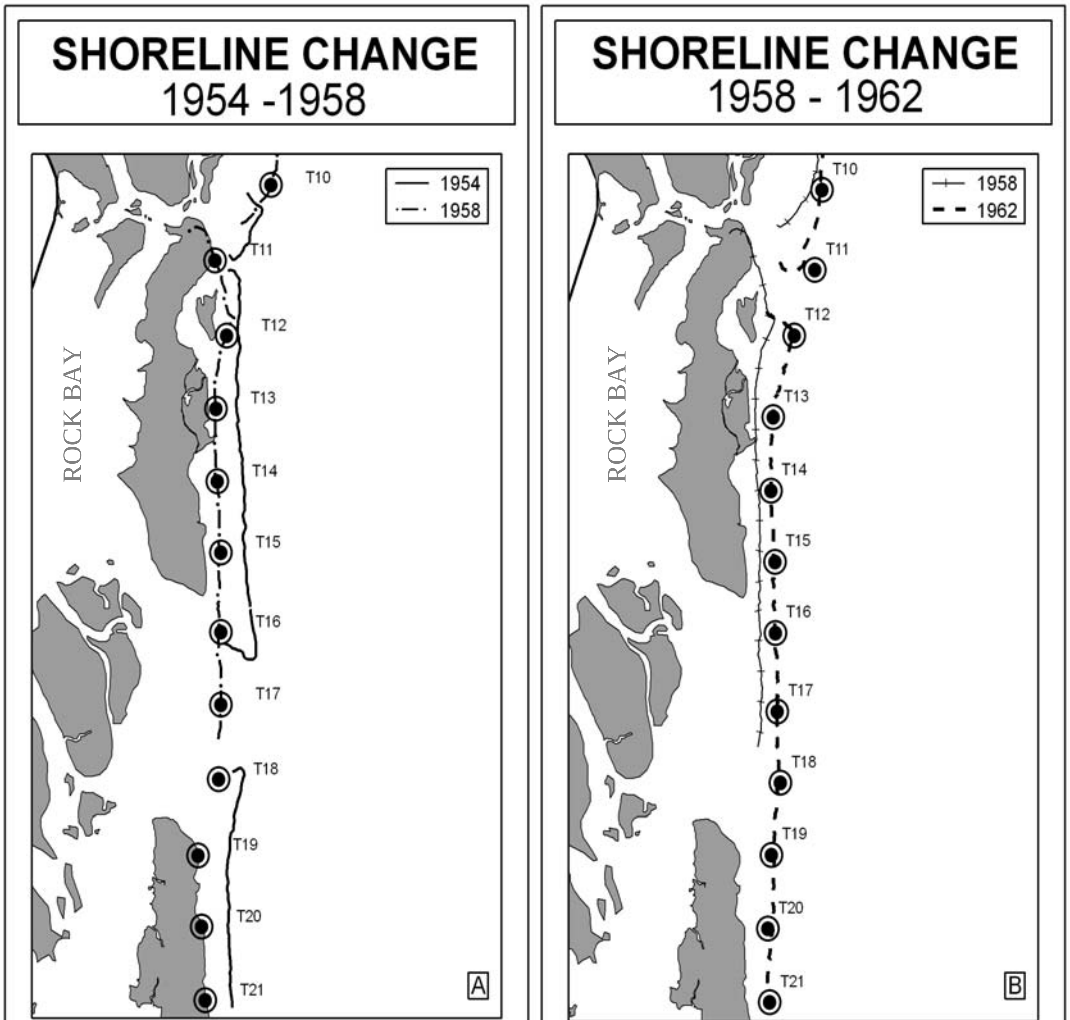
Shoreline Change Zone II

Shoreline Change Zone II, located in the southern portion of the study area, is 5.5 km long (Figure 7). The reach is bounded by T9 in the north and T21 in the south. SCZ II is generally characterized by a prograding shoreline and has undergone the most significant shoreline changes within the study area.

During the period 1945 to 2005, the shoreline along eleven of the twelve transects within SCZ II prograded (Figure 12 and Table 6). The net accretion along SCZ II for this period was 69 m, at a rate of 1.2 m/yr. The most significant changes occurred along T13, with the shoreline moving seaward 155 m (2.6 m/yr). The least amount of change was observed along Transect 21, where the shoreline accreted 0.3 m/yr, totaling 17 m.

The most significant period of progradation along SCZ II occurred between 1958 and 1962 (Figure 15). Net shoreline accretion along the reach was 92 m, adding 24 m/yr. The largest change occurred along T11, where the shoreline prograded of 340 m. In addition, during the period 1945 to 2005, shoreline change of no less then 100 m was observed along the portion of Federal Beach south of T11.

However, there are several periods from 1945 to 2005 where net erosion along SCZ II is observed. The most significant shoreline change occurred from 1954 to 1958, when the entire SCZ II reach receded landward (Figure 15). Net shoreline change along this portion of Federal Beach was -66 m, eroding 19 m/yr. The greatest change, -227 m,



SHORELINE CHANGE	
TRANSECT	1954 - 1958
10	0
11	0
12	-67.4
13	-150.1
14	-179.6
15	-168.9
16	-227.2
17	0
18	0
19	0
20	0
21	0
NET CHANGE	-66.1
EPR	-19.3

SHORELINE CHANGE	
TRANSECT	1958 - 1962
10	56
11	340.1
12	173.1
13	128.3
14	97.5
15	94.2
16	104.2
17	114
18	0
19	0
20	0
21	0
NET CHANGE	92.3
EPR	24.0

Figure 15. Shoreline change for SCZ II. (a) The largest net erosion occurred during the 1954-1958 survey period. (b) The greatest net accretion occurred during the 1958-1962 survey period.

was measured along T16. The least amount of erosion during this period was at T12, where -67m of shoreline change occurred.

DISCUSSION

Historic (pre 1945) changes to the hydrographic regime of the Old New Inlet system were considerable. Closure of the tidal connection between the Cape Fear River and New Inlet drastically decreased the tidal prism of the Old New Inlet system and caused appreciable morphological changes throughout the study area. From 1872 to 1985 the inlet system underwent a 5.25×10^7 m^3 reduction in tidal prism. Moreover, the reduction in the tidal prism of the Old New Inlet resulted in the formation of the Federal Beach barrier spit and the associated New Inlet A and B systems (SWAIN, 1993).

In addition, The Rocks have significantly influenced the evolution of the estuary backing the Federal Beach barrier spit. Conservative estimates by SWAIN (1993) suggest that 57% of ebb-tidal delta material was transported and redeposited in the backbarrier basin due to the artificial closure of Old New Inlet. Backbarrier volume gains from 1887 to 1985 were in the order of 10.93×10^6 m^3 at an average rate of 11.2×10^4 m^3/yr (SWAIN, 1993). Due to several early (pre 1880) failed attempts to mitigating the shoaling of the CFR by Old New Inlet's flood-tidal delta sediments, the estuary of the Federal Beach barrier was partially segmented into two tidal basins, “The Basin” and “Rock Bay” (Figure 1). Natural and artificial boundaries between these estuarine basins have decreased the hydraulic connectivity between the two compartments and have resulted in numerous and ever changing backbarrier channel configurations. The contemporary changes (post 1945) to the physical parameters, IMW and migratory habit, of the New

Inlet systems, and the subsequent planform changes occurring along the Federal Beach barrier spit were ultimately a result of the position of the New Inlet system with respect to the geometry of the two backbarrier tidal basins.

New Inlet Morphology

Although two inlet systems were present, only New Inlet B opened and closed during the study period 1938 to 2005. Thus, New Inlet B will be the system discussed herein. The migration of the New Inlet B system along the Federal Beach spit has resulted in significant changes to the barrier shoreline. Understanding the physical processes and environmental changes influencing the migration of the New Inlet system is of paramount importance when discussing the evolution of the barrier planform.

In addition to wave and tidal processes, there are many other external controls on tidal inlets including sediment supply, backbarrier basin geometry and sedimentation history (FITZGERALD, 1996). Specifically, the variability of the estuarine tidal basins and the hydraulic parameters found throughout the backbarrier environment are reflected in the dynamic behavior of the New Inlet system.

During the period from 1944 to 1999 the IMW and migratory habit of New Inlet B has been highly variable. There have been periods of rapid migration, 247 m/yr (1945-1949), as well as periods of relative stability, 6 m/ yr (1987-1990). Concurrent with these variations in migration rate, have been changes in the inlet's size, ranging from 335 m wide (1976) to 30 m wide (1998). When these two inlet parameters, IMW and migration rate, are plotted over time there seems to be an inverse relationship between the two (Figure 16). For example, between the years 1976 and 1992 the general trend of the system is a high IMW value and a low migration rate. Conversely, between 1992 and 1998 the trend of the system is a low IMW value and an increased migration rate.

However, when the two parameters are plotted against each other and correlated, the degree of association is low, with an r value of only .354 (Figure 16). The weak association between the two inlet parameters may be the result of several different factors. First, due to the limited availability of aerial photography in the area, only 17 data points were measured over a sixty year period. An increase in the number of points within the data set may result in a more representative sample and a stronger association between the two variables. Moreover, there is not a concurrent relationship between the two parameters. A response lag exists between a change in the size of the system, and a change in the behavior of the system. For example, there is a period of adjustment within the system between a decrease in the size of the inlet system and an increase in the migration rate. It is assumed that with a more robust data set the association between the two inlet parameters would be more readily observed and appear stronger. In addition, numerous studies conducted within southeastern North Carolina, including SWAIN (1993) and Cleary and FITZGERALD (2003), have found that changes in the size of an inlet system strongly correlate to changes in the tidal prism of the system.

By examining the evolution of the backbarrier environment, changes in the nature of the New Inlet system are found to coincide with changes in the tidal channel configuration and the area of the backbarrier bays. In 1945 New Inlet B was located along the northern portion of the barrier spit approximately 2.5 km south of the Fort Fisher Historic Site (Figure 8 & Figure 17). In this location New Inlet B had the strongest tidal connection to The Basin, a backbarrier bay approximately 17 km^2 in size. However,

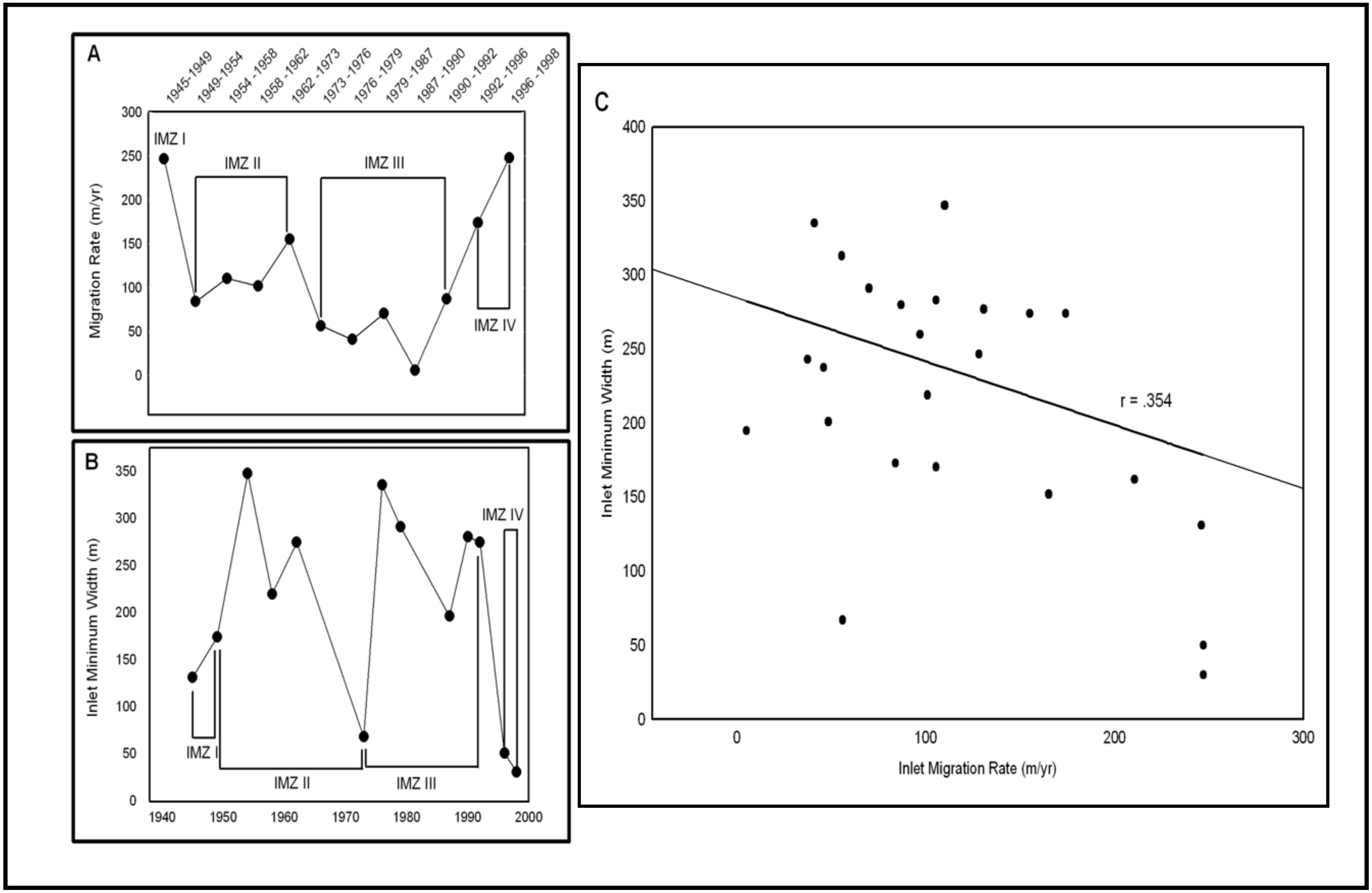


Figure 16. Plot of (a) migration rate over time (b) IMW over time and (c) IMW vs migration rate.

the hydraulic connection to the backbarrier during this period was reticulated and segmented by numerous subaerial marsh islands. In addition, within The Basin, moderate shoaling of the feeder channels was assumed to be further retarding the overall tidal prism of the New Inlet B system. Moreover, during this period New Inlet A was still open and continued to have a stronger hydraulic connection to Rock Bay; a significantly larger bay then The Basin, with an area of 35.5 km. Both of these systems in 1945 are relatively healthy, with moderately efficient drainage occurring through both inlets.

By 1962 the New Inlet B system was located 2.2 km further to the south along Federal Beach, having migrated at an average rate of 140 m/yr (Figure 17). During this 17 year period the minimum width of New Inlet B increased from 131 m (1945) to 274 m, suggesting an overall increase in the tidal exchange of the system. However, converse to an increase in the size of the inlet system during this period, is a 2 km^2 reduction in the overall area of The Basin bay to 15 km^2 and a fifty percent increase in the area of subaerial tidal marsh in the backbarrier. The increase in the tidal exchange of the New Inlet B system is likely due to the closure of the New Inlet A system sometime between 1956 and 1959. Once New Inlet A closed, the remaining inlet system, New Inlet B, was the only conduit for tidal exchange between the two backbarrier bays and the open ocean. In multi-inlet systems DAVIS and BERNARD (2003) have found that the closure of one inlet resulted in an increase in the tidal prism of the remaining open inlets in the system. An increase in the size and stability of the system, despite the decrease of the bay area and the increase of subaerial marsh growth in both basins; indicates that the combined effluence of The Basin and Rock Bay increased the hydraulic flow through the inlet.

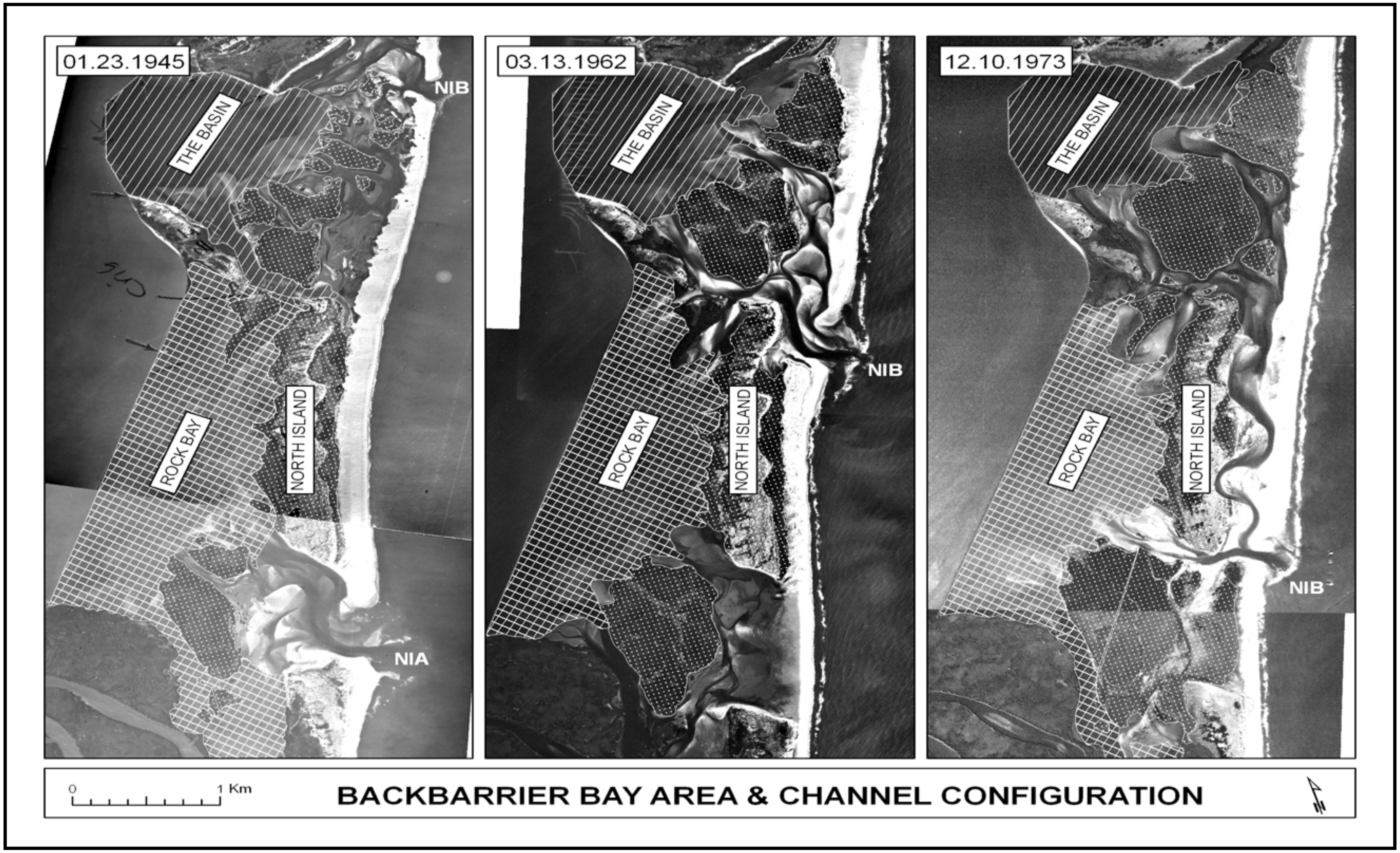


Figure 17. Representative aerial photographs showing the migration and backbarrier configuration of the New Inlet B system from 1945 to 1973.

In addition to backbarrier bay size, the hydraulic efficiency of the main feeder channel, as characterized by the channel's length and width, is a significant factor influencing the overall nature and behavior of the inlet system. Elongation of the inlet channel increases frictional resistance of tidal flow thereby reducing tidal range (FITZGERALD *et al.*, 2001). This influence is readily observed during the period 1962 to 1976. As the New Inlet system continued to migrate south along the Federal Beach barrier spit, direct tidal flow to both of the bays in the backbarrier is blocked by North Island (Figures 17 & 18). To maintain a hydraulic connection between the backbarrier and the open ocean, as the inlet continued to migrate along North Island, the main inlet channel became elongated and sinuous. By skirting the backbarrier island the elongated inlet channel is inefficient and tidal exchange through the inlet is restricted by the increased friction along the channel. In 1962 the inlet channel is approximately 1148 m long and the IMW is 274 m. By 1973 the channel length has increased three fold to 3458 m and the IMW has decreased to 68 m (Figure 17). Moreover, the decreased tidal flow through the inlet resulted in an increase in sedimentation within the inlet and backbarrier channels, further reducing the hydraulic efficiency of the system. The marsh development in Rock Bay between 1962 and 1973 increased by approximately 8 km^2. The growth of marsh in the backbarrier in concert with the increase in channel shoaling is further evidence of a reduction in the magnitude of the tidal prism of the system.

Further highlighting the relationship between inlet dynamics and the backbarrier environment are the morphological changes that occurred between 1973 and 1976. New Inlet B dramatically increased in width from 68 m to 335 m. However during this same

Figure 18. Representative aerial photographs showing the migration and backbarrier configuration of the New Inlet B system from 1973 to 1992.

period the inlet channel migrated only 146 m (Figure 18). With the inlet channel in approximately the same location and the inlet width increasing five fold, one might suggest that inlet location has little influence on the overall morphology of the system. However, further examination of the data set implies the contrary. The position of the 1973 and 1976 inlet systems are just beyond the southern most extent of North Island, with an unobstructed connection to Rock Bay. Examination of the aerial photographs and future trends of the inlet system from 1973 to 1992 indicates a long period of decreased migration rates with New Inlet B migrating only 670 m in 20 years while maintaining a minimum width of no less than 200 m. The data suggest that the morphological changes taking place between 1973 and 1976 are a rapid response to the increased tidal flow through the inlet caused by a more efficient channel alignment with respect to the configuration of the backbarrier. Moreover, from 1973 to 1976, the aerial imagery indicates an increase in the area of Rock Bay, growing from 27 km^2 to 33 km^2, and a decrease in channel shoaling; indicating resurgence in the tidal prism of the system and an overall increase in size of the inlet system. It is clear that once an efficient hydraulic connection between the backbarrier and Onslow Bay is established, the size and stability of the New Inlet system dramatically increases (Figure 18).

The New Inlet B system maintained a strong hydraulic connection and showed evidence of a relatively large tidal prism until 1992, when inlet migration, caused by the dominant southerly longshore current, again began to result in channel elongation (Figure 19). The system continued to have a strong tidal draw in 1992 with an IMW of 274 m, and a stable backbarrier area of 32 km^2. However, by September 1996 New Inlet B began to show signs of closure. Migrating 800 m in four years, in 1996 New Inlet B is again backed by a large area of marsh (Figure 19). Similarly to when the inlet was backed by North Island, the main feeder channel became elongated and sinuous. The channel length grew by 1828 m as the associated increase in frictional drag continued to reduce the efficiency of the system. A decreased tidal flow through the inlet is evident in the drastic decrease of the IWM to 50 m. By March of 1998 the inlet migrated an additional 372 m and the channel length increased to 2438 m. Shoaling within the inlet throat significantly restricted the tidal flow, further reducing the IMW to only 30 m. At this juncture the system is in the final stages of closure. In March of the following year (1999) the system had completely collapsed and the main inlet channel had shoaled closed, with no tidal exchange occurring between the backbarrier and Onslow Bay.

Both New Inlet A and B closed within a couple hundred meters of each other. However, unlike when New Inlet A closed, there is no other system open at this time to recapture the tidal exchange of the closed system, and absolutely no tidal exchange occurring between the backbarrier bays and the ocean. Obviously there are numerous physical factors acting in concert to control the evolution of any given tidal inlet system. The relatively close proximity in which both of the New Inlet systems close is a strong indication of the impact that backbarrier has on the morphodynamic evolution of their associated tidal inlet systems.

Inlet Migration and Shoreline Change

The Federal Beach barrier spit is one of the few barrier systems in southeastern North Carolina whose planform has translated seaward. The uniqueness of this area is

Figure 19. Representative aerial photographs showing the migration and closure of the New Inlet B system from 1996 to 1999.

attributed to the civil works projects undertaken within the vicinity of the Federal Beach barrier complex.

The shoreline changes along Federal Beach are largely the result of the migration of the New Inlet B system along the barrier spit. The convex alignment of the pre-1945 shoreline has been reworked into a more linear feature by one of two mechanisms. First, the seaward movement of the Federal Beach barrier is the result of the realignment of the updrift shoreline associated with the migration of the New Inlet system (Figure 6). Secondly, shoreline erosion along the spit is the long-term result of the collapse of the Old New Inlet ebb-tidal delta and an overall deficit of near shore littoral material (Figure 5) (SWAIN, 1993).

This study has identified two Shoreline Change Zones. Over the period of this investigation, from 1945 to 2005, SCZ I is characterized by net erosion, while SCZ II is characterized by net accretion. On the whole, EPR calculations are useful for identifying long-term trends and evaluating low frequency changes. However, in this investigation the EPR values do not fully illustrate the impact of inlet migration on the study area shoreline. The scope and magnitude of influence the New Inlet B system has on the Federal Beach barrier spit is only fully realized when shoreline change values are examined in conjunction with inlet location.

The relationship between shoreline position and inlet migration is evident when examining the changes that occurred along the Federal Beach shoreline south of the 1945 location of New Inlet B. In 1945 New Inlet B was located immediately north of T7 (Figure 20). The southern migration of New Inlet along Federal Beach resulted in the seaward displacement of the updrift barrier planform. From 1945 to 1958 New Inlet B

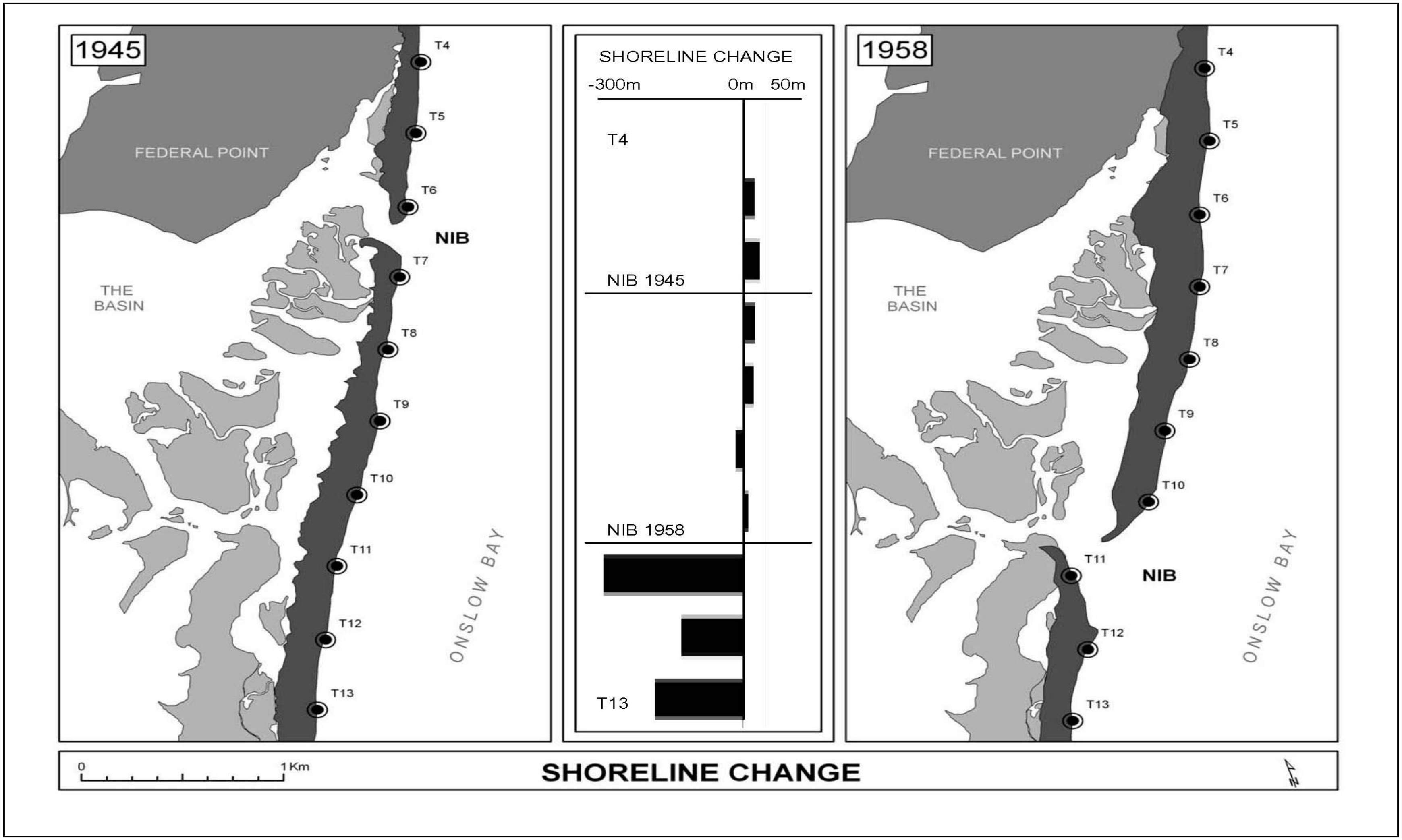


Figure 20. Barrier planform changes as New Inlet B migrates along Federal Beach from T6 to T11 (1945-1958). Notice positive shoreline change occurring along T7 to T10.

migrated 1.9 km south. Progradation of the shoreline occurred along three of the four transects (T7-T10) which New Inlet B migrated through (Figure 20). During this period, transects 7, 8 and 10 experienced 23 m, 20 m, and 10m of accretion respectively. The change experienced along these transects may appear to be small. However, when examining the average shoreline change, -170 m, for all of the transects located downdrift of the 1958 New Inlet B position, we see that the aforementioned updrift transects strongly depart from the significant erosional trend that characterizes the downdrift shoreline.

From 1962 to 1973 New Inlet B continued to migrate south along the Federal Beach barrier spit, relocating from T11 to just south of T15 (Figure 21). The average shoreline change for these transects was 131 m. The largest shoreline change, 200 m, occurred at T13, and transects 11, 12 and 15 all experienced approximately 100 m of accretion. Again, during this period the influence of the New Inlet B system is evident when the average updrift shoreline accretion is compared to the average shoreline erosion of -15 m occurring downdrift of New Inlet B.

The influence of New Inlet B on the shoreline of Federal Beach is further highlighted when one examines the overall shoreline change that occurred from 1945 to 1973 (Figure 22). During this period New Inlet B migrated 4.2 km from T7 to T15. The shoreline along each of these nine transects prograded an average of 92 m. Conversely, the downdrift barrier shoreline during this period eroded an average of 40 m.

Since the closure of New Inlet B in 1998 the entire Federal Beach shoreline, with the exception of the cell between T20 and T21, experienced erosion. The retrograding barrier spit has undergone an average of -7 m of change from 1998 to 2005. The closure

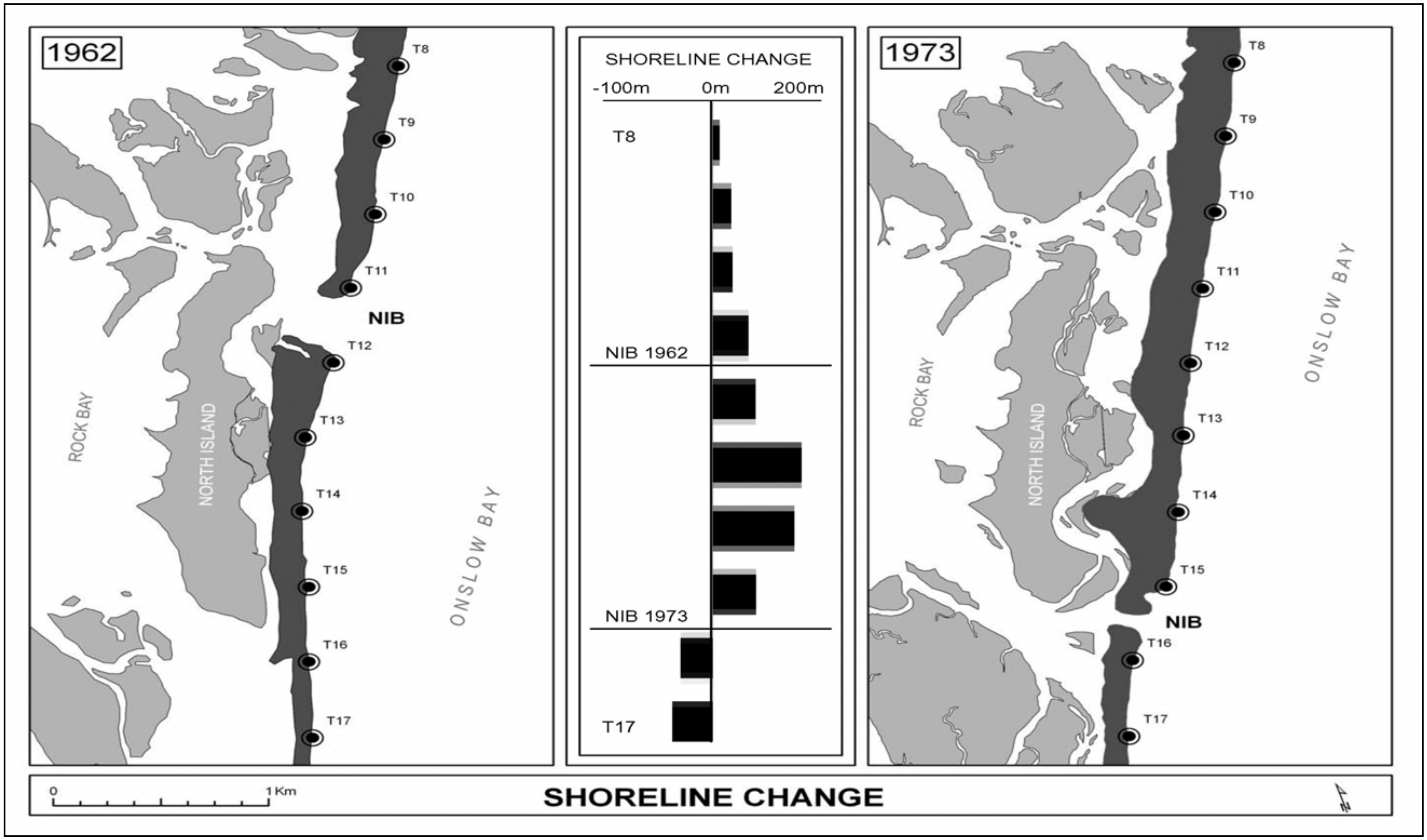


Figure 21. Barrier planform changes as New Inlet B migrates along Federal Beach from T12 to T16 (1962-1973). Notice positive shoreline change occurring along T12 to T15.

of the New Inlet B system has removed from the Federal Beach barrier spit complex the mechanism responsible for the progradation of the barrier shoreline.

Regional Context

The unique nature of Federal Beach and the associated New Inlet systems is readily apparent when the behavior of the barrier spit complex is compared to the changes occurring along regional barrier systems. The Federal Beach barrier spit is of significant interest due to the continued impact of the anthropogenic activities in the area on the evolution of the barrier planform.

Net shoreline change along Federal Beach for the period between 1945 and 2005 was 6 m, averaging 0.1 m of accretion per year. Shoreline change of this magnitude may not at first appear to be significant; however Federal Beach is the only barrier to experience net shoreline gains over this period within southeastern North Carolina. Surveys by the North Carolina Division of Coastal Management indicate that the three major barrier systems directly north of Federal Beach, Kure/Carolina Beach, Masonboro Island, and Wrightsville Beach, are all retrograding. The ocean front shoreline in these areas is eroding at an average rate of 1 to 3 m/yr (NCDCM, 2003). Even with artificial beach nourishment projects augmenting the natural erosion taking place the shorelines in these areas continue to retreat.

The migratory habit of New Inlet is also distinct when compared to other inlets found along Onslow Bay. The migration rate of New Inlet B during the period from 1945 to 1999 ranged from 6 to 247 m/yr, averaging 115 m/yr. The migration rate of Mason Inlet, another historically unstable inlet in the region, varied from 0 to 90 m/yr, with an

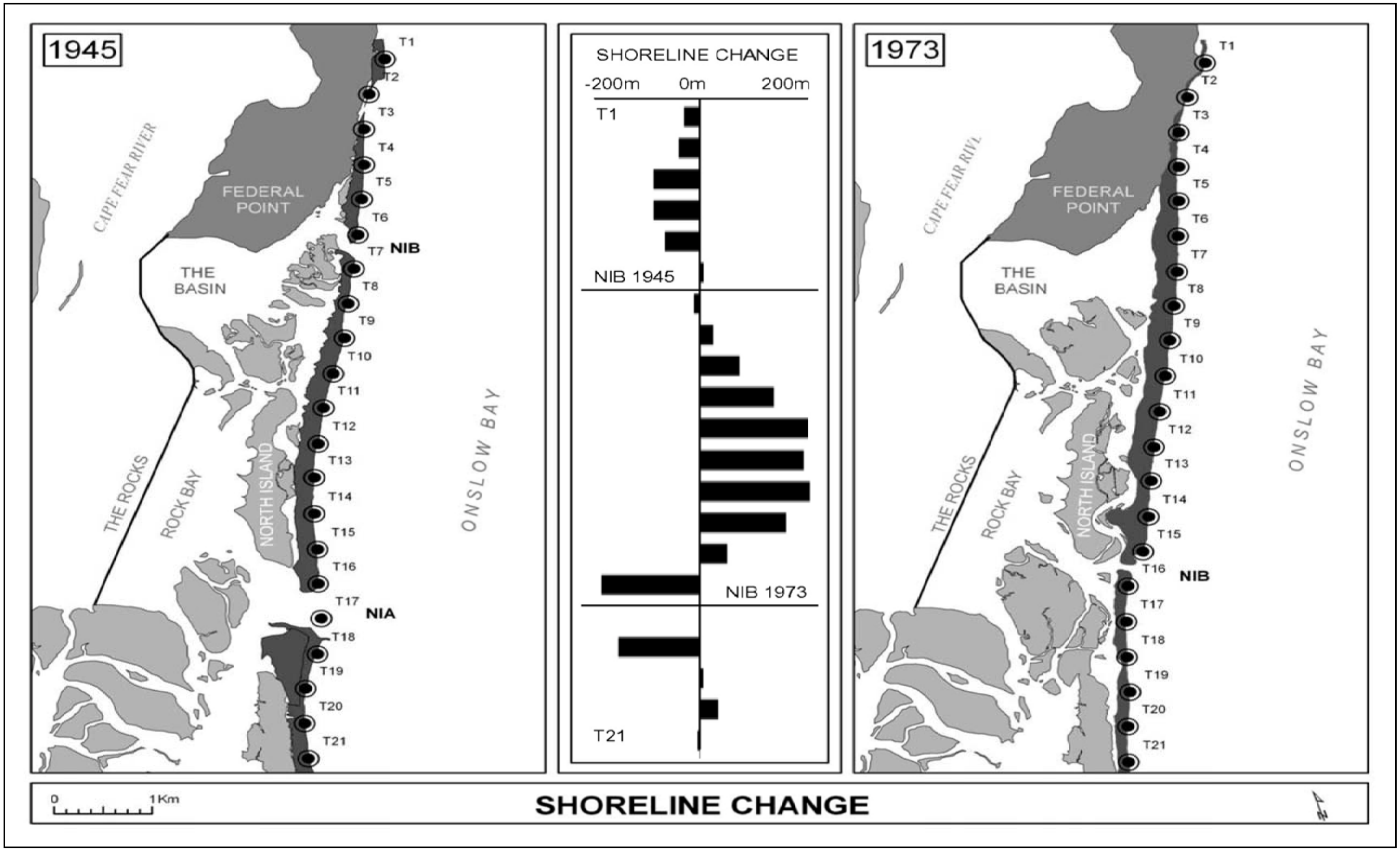


Figure 22. Barrier planform changes as New Inlet B migrates along Federal Beach from T7 to T16 (1945-1973). Notice positive shoreline change occurring along T8 to T15.

average rate of 50 m/yr (CLEARY and FITZGERALD, 2003). In addition Mason Inlet, from 1938 to 1996, migrated 2.1 km, whereas New Inlet migrated approximately 6 km (CLEARY and MARDEN, 2004).

Moreover, the influence of New Inlet on adjacent shoreline change is markedly different than that of Mason Inlet. The migration of New Inlet along the Federal Beach barrier has resulted in the accretion of the updrift shoreline by as much as 200 m. In addition, the migration of New Inlet has resulted in the seaward translation of the barrier planform and significant realignment of the entire 7 km barrier spit. By contrast, the influence of Mason inlet on the surrounding shoreline has been significantly less. During the period from 1974 to 1996 the updrift shoreline has eroded and average of 17.5 m. Also, the migration of Mason Inlet has influenced the shape of the shoulders, and approximately 1 km of ocean front contours, along the adjacent barrier islands.

Future Changes

Future shoreline change predictions based on the EPR and LRR calculations of the shoreline change along Federal Beach from 1945 to 2005 suggest that the overall barrier spit shoreline will prograde an average of 2.5 m over the next twenty five years. Similarly to the previous sixty years, the shoreline of Federal Beach can be divided into two reaches based on the forecasted change trends. Shoreline change zone I will continue to be characterized as a regressive zone. The average forecasted erosion for SCZ I is 32 m. Likewise shoreline change zone II is predicted to continue prograding, averaging 29 m of accretion over the next twenty five years.

This, however, is a very unlikely scenario for a number of reasons. First, the forecasted shoreline change along Federal Beach is based on two statistical computations, the EPR and LRR rates of change. The majority of the data, 54 out of 60 years, used in these calculations was derived from shoreline change data collected while New Inlet A and B were open. The inlet systems of the Federal Beach barrier spit complex are mechanisms for shoreline realignment and actively translated the barrier spit planform in the seaward direction. Since the closure of the last active inlet system in 1998 Federal Beach has been a retrograding barrier. The potential for barrier spit breaching and inlet formation in the immediate future is unlikely. The area most prone to breaching and where past inlet systems have formed, directly south of the spit attachment, has approximately doubled in width, 250 m (1938) to 500 m (2002), due to backbarrier sedimentation and marsh growth over the past sixty years.

Projected shoreline change values derived from EPR and LRR calculations for the shoreline change post inlet closure, from 1999 to 2005, indicate that the barrier spit shoreline will retreat an average of -30 m over the next twenty five years. During this period both shoreline change zones are forecasted to erode significantly. However this projected shoreline change is also unreliable due to the limited range of the 1999-2005 data set.

Furthermore, both of the projected shoreline changes based on EPR and LRR calculations do not factor in a change in sea level. The National Academy of Science projects that the global sea level will rise 5 cm to 12 cm rise over the next century. This is a relatively conservative projection, ignoring the possible occurrence of a major climatic catastrophe. The US Environmental Protection Agency and the Intergovernmental Panel on Climate Change (2007) both speculate that sea level could rise by as much as a meter along the eastern coast of the U.S. by 2100. Projections by TITUS (1991), suggest that a meter rise in sea level over the next century could translate to 100 m to 200 m of horizontal land loss in North Carolina alone.

Even with a conservative estimated change, the future impacts of sea level rise on the study area will be quite significant. A rise in sea level of only a couple of centimeters would threaten the structural integrity of The Rocks and drown backbarrier marsh growth, drastically increasing the size of the bay backing the Federal Beach barrier spit. Collapse of The Rocks would have disastrous results. First, the increase in backbarrier bay volume would undoubtedly result in a breach in the Federal Beach barrier during a major storm event and create a new inlet system. Resumed sedimentation of the Cape Fear River shipping channel would be the combined result of the new inlet system and the destruction of The Rocks. Again, coastal engineering structures would need to be constructed to mitigate the shoaling, at a sizeable cost to the state and county. The effects of such a structure on the backbarrier environment would result in further morphological changes of unknown magnitude along the Federal Beach barrier spit.

The Federal Beach shoreline is affected by the morphodynamics of adjacent beach complexes and substantial portions of the offshore and backbarrier. It is uncertain how much influence those areas will have in the future as they continue to endure changes induced by man and nature. Unfortunately such changes often appear subtle in the short-term and their capacity to promote major long-term shoreline changes are often underestimated.

Regardless of the reliability of the forecasted shoreline changes, it is clear that natural process will continue to erode the Federal Beach barrier spit. Sea level rise will also significantly contribute to the morphological evolution of the barrier planform and will likely cause changes requiring costly mitigation actions.

CONCLUSIONS

The Federal Beach barrier spit, from 1945 to 2005, experienced positive net shoreline change. The observed accretion is the result of the reconfiguration and realignment of the barrier spit planform due to the migration of the New Inlet B system. The migration of the New Inlet B system is in turn partially controlled by the configuration and hydraulic nature of the backbarrier basin.

From 1945 to 1999 the New Inlet B system migrated along the Federal Beach barrier a total of 6 km. Both the size and the migration rate of the system varied greatly over this period. Examination of the data suggested that there was a weak relationship between the changes in the migration rate of the system and changes in the IMW of the system. This relationship suggests that the magnitude of the overall hydraulic discharge of the system controls the relative stability the system. Moreover, variations in the hydraulic nature of the New Inlet B system can be related to the geographic location of the inlet along the Federal Beach barrier spit. Further examination of the Federal Beach barrier spit complex, highlights the influence of backbarrier basin hypsometry on the morphodynamic evolution of the New Inlet system and ultimately the configuration of the Federal Beach barrier spit planform.

Shoreline change along the barrier is not uniform. However, there are two general trends in the EPR calculated data for the period 1945 to 2005. Statistical analysis of the data indicates a zone of accretion and a zone of erosion. However, further examination of the shoreline change data for various eras within each zone revealed a great amount of deviation in the observed changes. When comparing the shoreline change trends of Federal Beach to the variations in the location of New Inlet B, it became evident that accretion of the shoreline typically occurs on the updrift side of the New Inlet B system. When shoreline change data was coupled with inlet location the pattern of updrift realignment is obvious. The migration of the New Inlet B system along the Federal Beach barrier spit has caused the realignment of the barrier planform, and has resulted in the progradation of the Federal Beach shoreline.

However, since the closure of the New Inlet B system in 1999 the Federal Beach barrier spit has undergone consistent erosion. Future changes along Federal Beach will depend significantly upon the reopening of another tidal inlet system and the subsequent morphodynamic changes it imparts on the barrier spit.

The morphodynamic evolution of the Federal Beach barrier spit is the result of complex interactions between man and nature. Subtle changes in the physical mechanisms and environmental variables of the system will continue to have drastic long-term effects on the barrier spit planform. Continued long-term monitoring is essential to the implementation of effective coastal management policies in the area.

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